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AFTAC Project VELA T/7701

FINAL REPORT
ADVANCED ARRAY RESEARCH

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TEXAS INSTRUMENTS INCORPORATED
Science Services Division
P.O. Box 5621
Dallas, Texas 75222

Contract:	F33657-67-C-0708-P001
Contract Date:	15 December 1966
Amount of Contract:	$625,500
Contract Expiration Date:	14 December 1967

Sponsored by

ADVANCED RESEARCH PROJECTS AGENCY
Nuclear Test Detection Office
ARPA Order No. 624
ARPA Program Code No. 7F10

Prepared for

AIR FORCE TECHNICAL APPLICATIONS CENTER
Washington, D.C. 20333

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ACKNOWLEDGMENT

This research was supported by the
ADVANCED RESEARCH PROJECTS AGENCY
Nuclear Test Detection Office

under
Project VELA UNIFORM
and accomplished under the technical direction of the

AIR FORCE TECHNICAL APPLICATIONS CENTER
under Contract No. F33657-67-C-0708-P001

ABSTRACT

A qualitative summary of the four principal tasks pursued during 1967 is presented. Quantitative results and more detailed descriptions of the various experiments are presented separately as a series of special technical reports. An appendix to this report lists these special reports with their abstracts.

Principal tasks reported are studies of continuously adaptive data processing systems; use of multicomponent arrays of mixed sensor type; signal and noise characteristics across a worldwide seismic network; and new approaches to the intra-array signal equalization problem.

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LIST OF ILLUSTRATIONS

LIST OF ACRONYMS

CPO	Cumberland Plateau Observatory
LASA	Large-Aperature Seismic Array
LP	Long period
LRSM	Long-Range Seismic Monitor
MCF	Multichannel filter
MSE	Mean-square-error
NS	Noise sample
NSB	Noise sample B
SNR	Signal-to-noise ratio
SP	Short period
SSA	Signal sample A
SSB	Signal sample B
TFO	Tonto Forest Observatory
USC&GS	United States Coast and Geodetic Survey
WMO	Wichita Mountain Observatory

SECTION I

INTRODUCTION

The best data available for detecting, locating, and identifying seismic events are provided by proper design and use of seismic arrays. Project VT/7701 has been directed toward improving array technology through theoretical and empirical studies of seismic noise and signal characteristics and development of advanced data processing and analysis techniques.

This report is a qualitative summary of the objectives and results of the several experiments conducted, the interpretation of these results, and the conclusions. More comprehensive and detailed documentation of these experiments is presented separately in the special reports.

A. TASKS

The five experimental tasks undertaken during the 1 year covered by this report, as specified in the statement of work, are as follows.

- Using an ensemble of seismic array network data to be furnished by AFTAC, investigate bodywave noise on a coherent worldwide basis. Investigate interarray equalization problems. Study methods of combining the subarray output for network signal extraction. Investigate the capabilities of a worldwide network for resolving events closely spaced in time and space.
- Continue investigations of multielement system studies to determine possible new combinations of sensors for noise reduction. Study methods of specifying, for given noise fields, the optimum multisensor system for noise reduction, with the desired result a set of guidelines for array design. These guidelines should include, but not be limited to, the type of sensors required and, for an array, the size and geometry, subject to the constraints of practicability.
- Theoretically investigate methods of implementing continuously adaptive systems for application to time-varying noise fields and postdetection processing. Any system that can be simulated off-line should be evaluated using suitably characteristic data.

- Investigate the effects and methods of reducing locally generated noise. The effects of such non-plane wave fields on multichannel filter design should be evaluated.
- Continue studies of the instrumental equalization problem. Apply any new techniques available for studying instrumental equalization and evaluate the effectiveness of such techniques.

B. SUMMARY

All tasks and subtasks are reported in detail in 14 special reports, the summaries of which are contained in the appendix. The intent of this final report is to provide a comprehensive, though qualitative, summary of the principal experiments and their results.

In addition to the final report and special reports, four quarterly and eight monthly reports recording the progress of this research have been published.

1. Network Studies

Coherently-processed seismic arrays are not limited to any particular size; arrays with diameters of 3 to 200 km have been used to extract and identify seismic events.

As the size of the array increases, many advantages accrue but many new problems also arise. Expansion of the array to encompass the whole earth should provide the ultimate in detection threshold level, event resolution, and event classification. Such a worldwide array ideally would consist of a network of one or more large-aperture arrays and a greater number of smaller high-quality arrays. The wide variation in ambient noise and signal characteristics expected over such an extensive network undoubtedly would require new data processing and analysis techniques. The first task (network studies) described in this report was initiated to provide an initial characterization of the seismic noise and signals as recorded by a network and an interpretation of how to capitalize on these characteristics in order to improve nuclear-surveillance capability.

Simultaneous recordings of several signals and several noise samples across a network consisting of 10 VELA and LRSM stations have been obtained and analyzed. Power-density spectra of both short- and long-period noise are computed to measure the time and space variability of the noise field. Interstation coherence measurements for long-period noise reveal virtually no coherence, indicating that time-shift-and-sum processing is optimum for network signal extraction. High-resolution frequency-wavenumber spectra are computed for two noise samples from each array station. Surface-wave noise is found to predominate at all stations except TFO and NPNT and to be highly correlated with storm activity along the perimeter of the same continent. Bodywave noise correlatable with storm activity is seen at TFO and NPNT but is rarely seen at the surface-wave noise-limited stations.

Studies of short-period signal similarity across the network reveal considerable variation in P-wave amplitude and waveform, which is not easily correctable with equalization filters. Improvements in signal-to-noise ratio over simple beamsteering are obtained with weighted beamsteering. The ability of even a very limited network to resolve two events occurring very close in space and time is demonstrated. Several approaches to network processing for depth-phase enhancement show promise.

2. Multielement System Studies

A procedure for calculating the crosspower spectra between two seismometer outputs, corresponding to assumed frequency-wavenumber models of the seismic activity, has been developed. The technique is applicable to sensors separated both vertically and azimuthally, to sensors measuring various aspects of the seismic activity such as displacement or strain, and to the different modes of seismic propagation. A program embodying these results would be useful in the design of multichannel filters for multicomponent arrays, since adequate measured statistics for the signals and noise are frequently not possible to obtain.

A theoretical comparison of beamsteer and multichannel-filter array processors over the frequency range 0.0 to 0.25 Hz has been made. The problem considered is the extraction of a directional signal from ambient noise having a dominant component that is isotropic and is also propagating at 3 km/sec; this problem is relevant to long-period arrays where the signal of interest and the predominant noise propagate in the fundamental Rayleigh mode. The multichannel filter processor proves superior at all frequencies but is significantly so only below 0.05 Hz where neither processor yields $\sqrt{N}$ SNR improvement. Interestingly, above 0.05 Hz, the improvement of either processor oscillates substantially about $\sqrt{N}$. This behavior is clearly caused by the aliasing properties of the hexagonal-grid array geometry.

Analysis of the high-resolution K-line wavenumber spectra computed for each of three seismometer lines in the 10-element short-period array at WMO reveals broadband surface-wave energy (0.2 to 1.0 Hz) coming from the northeast (probably generated by lakes a few kilometers away in that direction). Mantle P-wave energy (apparent velocity greater than 8 km/sec) also is found to be appreciable in this frequency range.

Multichannel filters have been designed for an experimental WMO array consisting of two rings of six radially oriented horizontal seismometers concentric with a vertical seismometer. Motivating this experiment was previous theoretical work indicating that arrays of this type are useful in the extraction of compressional signals from surface-wave noise. Over the frequency range of 0.0 to 3.0 Hz, the average SNR improvement of 3 db is less than expected. Examination of the horizontal seismometer traces indicates severe random-noise contamination.

3. Studies of Adaptive Systems

The design and application of fixed multichannel filters to time-varying noise fields is known to be less than optimum. Therefore, the use of adaptive filters which can vary their responses as the noise field changes is indicated.

A theoretical and empirical study of the performance and properties of a particular class of adaptive multichannel filters was initiated this past year. The rate of adaptation and the convergence of these filters were initially studied by comparing adaptive and fixed Wiener multichannel prediction filters.

Adaptive filters are shown to perform equally well for data approximately stationary and significantly better for data known to be nonstationary. The effects of redundant sampling have been examined and are found to result in a high level of false gain when badly oversampled data are simulated. Extension of the adaptive technique to problems in signal extraction has been considered.

4. Noise from Near Sources

Study of the effect of noise from sources so near the array that the assumption of space stationarity is invalid has been continued. A theoretical noise model in which wavefronts are circular and there is attenuation as the wavefronts traverse the array has been developed. Loss in filter performance for a filter applied to space-stationary noise when designed from this nonstationary noise model has been found to be insignificant.

Since adaptive filtering has shown promise for dealing effectively with nearby noise sources, this study has been merged with the adaptive processing study, which is expanded to include nonspace-stationary noise problems.

5. Intra-Array Equalization and Statistical Studies

A study of the distributions of two measures of multichannel filter performance has been performed. One statistic measures the ratio of the multichannel-filter-design regression error to the mean-square-error (MSE) of the optimum filter. The other statistic measures the ratio of the MSE of the estimated filter to the MSE of the optimum filter. Graphs which are presented specify, as a function of the number of channels, the amount of measured noise required to design filters of a given quality. Both statistics are shown to be independent of one another and of the noise covariance matrix.

The concept of group coherence (coherence between two sets of data channels) is reexamined in terms of the information contained in the group-coherence MCF's concerning seismometer inequalization and noise field structure. The technique, although found to lack sufficient wavenumber resolution for isolating coherent energy sources and detecting the second-order effects introduced by seismometer inequalization, is highly valuable as a measure of multichannel coherence.

SECTION II
NETWORK STUDIES

Network studies are directed toward effective utilization of a collection of seismic stations as a coherent worldwide seismic network to enhance capabilities for seismic-event classification. These studies, initiated 1 year ago, examine signal and noise characteristics as seen at the network level.

Presented in this section are summaries of the studies. Three special reports more fully and quantitatively describe the preliminary analysis of

- Ambient noise characteristics at the network level[1,2]
- Network signal characteristics and coherent signal processing[3,4]
- The role of the array station as an element of a worldwide network

The network consists of: VELA seismological observatories TFO and CPO, LRSM array stations OONW, NPNT, GGGR, LZBV, and HWIS; and LRSM sites ADIS, RKON, and DHNY. Figure II-1 shows locations of the stations. The station distribution, in effect, limits the network to northern-hemisphere coverage. Only vertical-component instruments are used.

Data for the study include signal and noise samples simultaneously recorded across the network. Long- and short-period noise samples and short-period signals have been analyzed. During the noise and signal characterization studies, all results have been evaluated for their significance in improved signal detection, source location, and source identification.

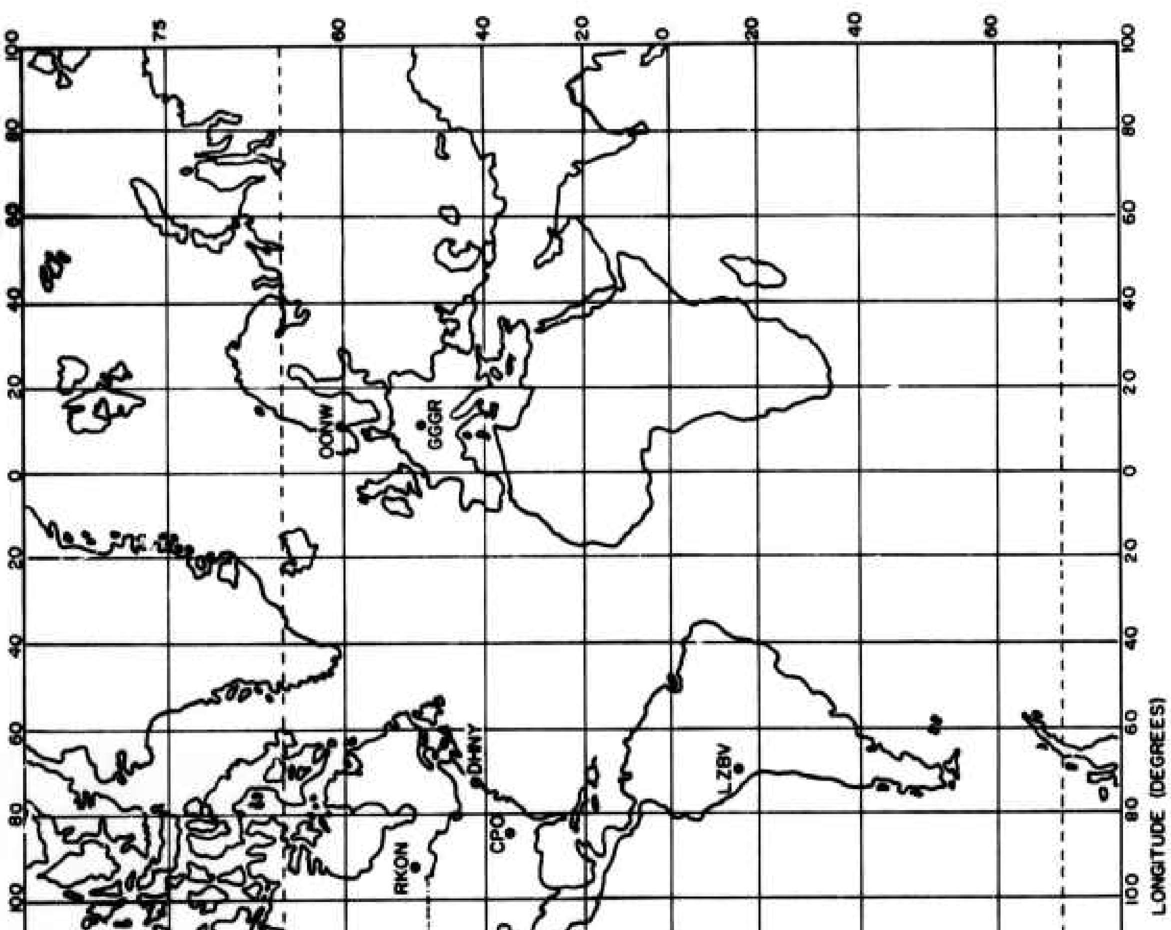

Figure II-1. Geographical Location of Network Stations

The network studies performed represent a preliminary examination of network operation using a limited data ensemble that reflects neither year-round nor worldwide conditions. The network itself is highly limited in terms of station quantity and distribution. Tentative conclusions regarding both network operation and station function as a network element are subject to continued investigation.

An operational concept of network processing has begun to take shape, however. Initial detection of events appears to be a subarray function, with the network operating in an iterative role, combining station estimates and refining location and timing information. Further postdetection processing at the station level, therefore, should be performed with the updated information. The process can be fully automated and yet subject to human judgment, as a man-machine discourse is visualized at the network level.

A. NETWORK AMBIENT NOISE ANALYSIS

1. Objectives of Study

The primary objective of the network ambient noise study is to characterize the seismic noise observed at the network level. To achieve this rather broad goal, answers to several fundamental questions are sought:

- How does the noise power vary as a function of frequency, time, and geographical position?
- What are the dominant propagation modes observed for coherent seismic noise?... what are the sources of this noise?
- To what extent are the array stations in the network limited by bodywave noise?
- How coherent across the network is that component of the seismic noise which is coherent at the station level?

Answers to these questions are sought in several ways. An ensemble of five noise samples, recorded between 12 August 1964 and 29 January 1965, is analyzed with power-density spectra and coherence measurements. Also, two noise samples reflecting widespread storm activity are analyzed with frequency-wavenumber spectra. Bodywave noise levels are estimated by comparing the input and output of processing procedures such as straight summing, Wiener disk-model multichannel filtering, and adaptive filtering.

2. Results and Conclusions

Analysis of the noise power-density spectra reveals large variations in noise level with geographic position, frequency, and time. These variations are well-correlated with the presence (or lack) of regional storm activity.

Certain seasonal trends are evident. Noise power levels are usually lower during the summer; across the network, they were uniformly lower during the sample on 12 August 1964 (a relatively calm day). Noise power levels are usually noisy during the winter; all stations were unusually noisy during the sample of 6 November 1964 (a day with widespread storm activity across the northern hemisphere). Ocean wind-wave height and swell height charts correlate well with surface weather charts for these time periods and provide circumstantial evidence for postulating coastal surf action as a significant noise source.

In general, station short-period noise power-density spectra are found to be seismically valid between 0.2 and 2.0 Hz. The bulk of noise power and the largest variations in level are observed in the 0.2- to 0.5-Hz microseismic band. An exception is GGGR which is dominated by noise power in the 1.4- to 2.5-Hz band: whether this energy is primarily seismic has not been established.

Figure II-2 shows absolute power-density levels observed at 1.0 Hz for available noise samples at each station. TFO and NPNT have relatively low noise levels, while GGGR, OONW, and ADIS are relatively noisy sites. Noise-level fluctuations with time at each station are considerable and coincide with the proximity of strong storm activity.

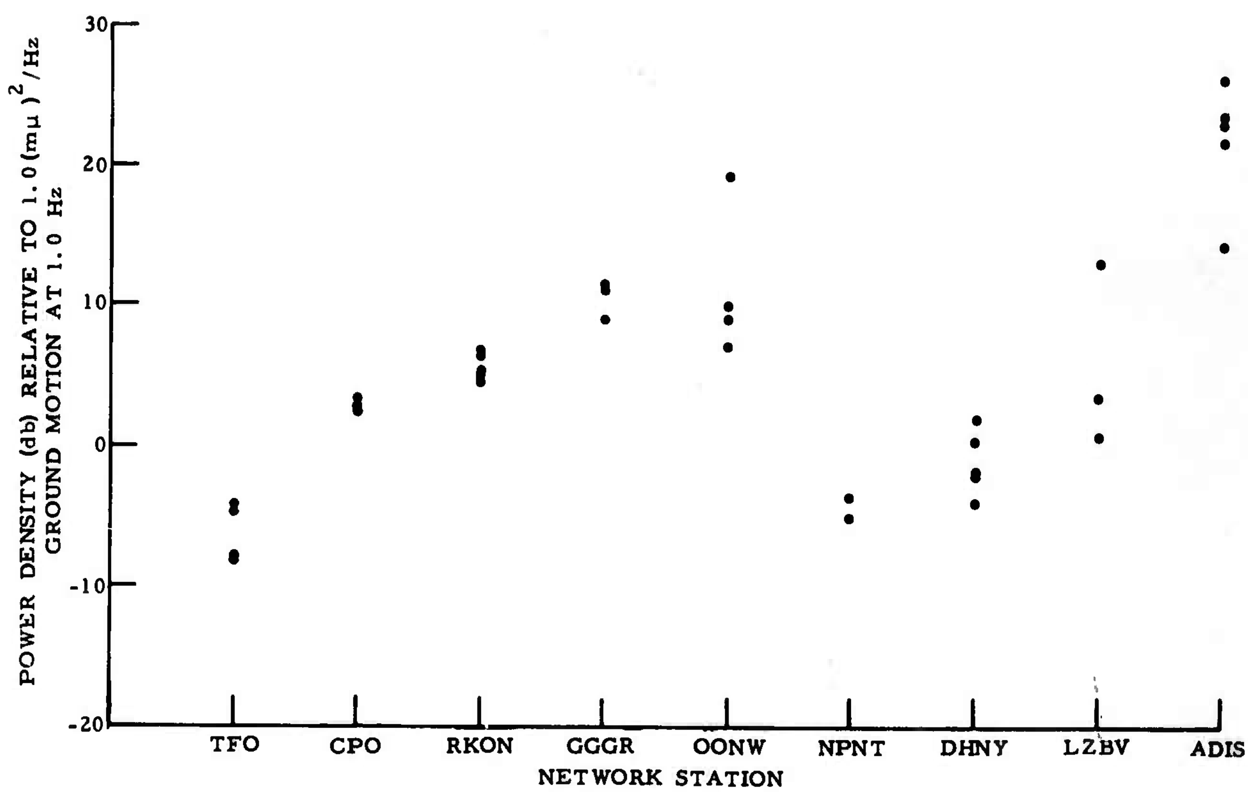

Figure II-2. Station Ambient-Noise Power-Density Spectral Levels at 1.0 Hz for Several Network Noise Samples

Figure II-3 presents power-density spectra computed for four 6.67-min samples at OONW. Power-density levels at 1.0 Hz vary from 7 to 19 db. Larger weather-related variations are seen in the 0.2- to 0.5-Hz microseismic band. Above 2.0 Hz, the spectra exhibit numerous lines and a generally flat level; this energy appears to be primarily system noise.

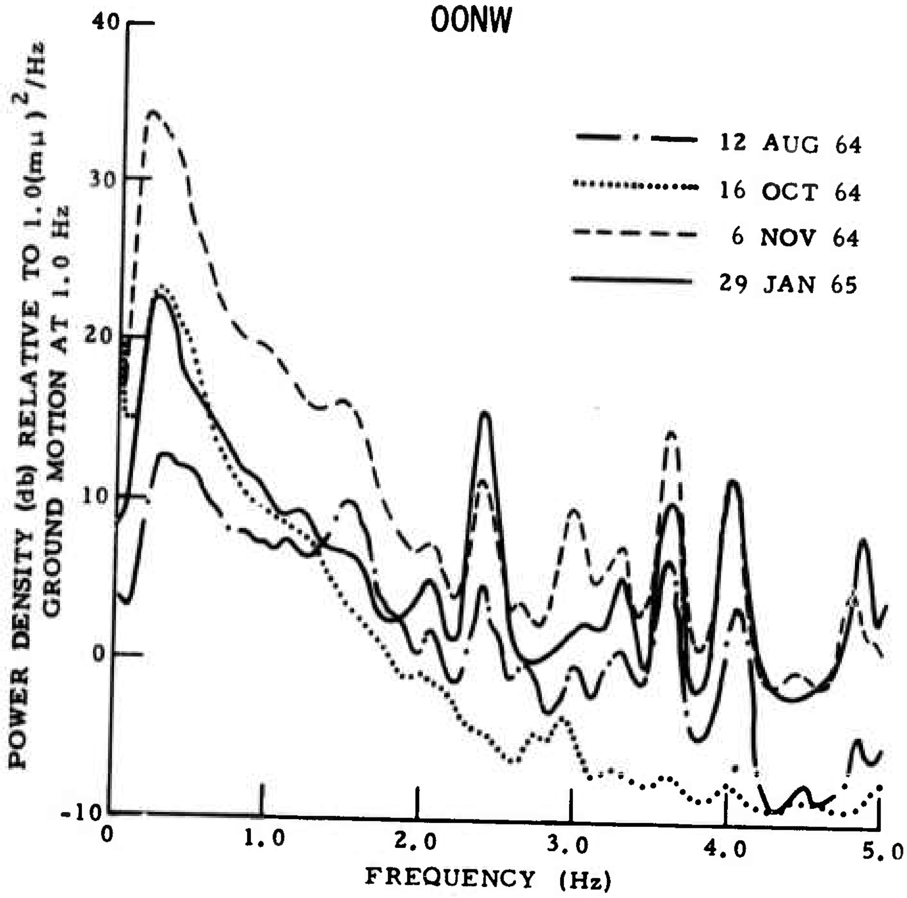

Figure II-3. Ambient-Noise Power-Density Spectra at OONW

An exception is the 16 October 1964 sample which is digitized from uncompressed FM tape; the others are from compressed tapes. Broadband rms noise-level estimates made for these samples indicate ground motion of 3 to 19 mμ. Similar estimates made from bandlimited outputs (0.8 to 2.8 Hz) indicate ground motion of 2 to 8 mμ. OONW noise levels appear somewhat higher than those at CPO.

Long-period noise power-density spectra also are computed for several network stations from two noise samples. Overall data quality is poor; however, the spectra appear seismically valid between 0.03 and 0.2 Hz. In general, the station spectra reflect dominant spectral peaks at approximately 0.06 Hz and lesser peaks near 0.12 and 0.2 Hz. Spectra are corrected to units of absolute ground motion at 0.04 Hz; power densities, surprisingly consistent among stations at this frequency, average approximately 45 db. Comparison with LASA long-period spectra[5] (which represent analysis of considerably higher-quality data) results in general agreement in both frequency of observed peaks and overall spectral levels. The long-period spectra's apparent stability (and general lack of sensitivity to regional noise sources) at 0.04 Hz should be studied further to explain this behavior and to establish the source of this energy.

Broadband spectral estimates are formed by joining absolute long- and short-period spectra for each station. Figure II-4 shows broadband estimates for CPO. The spectra appear dominated by microseismic energy between 0.1 and 0.3 Hz. Also observed in this band is the largest variability, which is related to nearby storm activity (tropical storm Isabel located off Cape Hatteras during the 16 October 1964 sample) and to the relatively poor estimates (both short- and long-period instrument responses being low in this frequency range). The power indicated below 0.03 Hz is not believed to be seismic but to be due to coupling with atmospheric-pressure fluctuations.

Interstation coherences computed for the long-period data reveal no usable network coherence. A few coherent peaks significantly above the expected value for random correlation are observed; these are generally above 0.1 Hz and are seen only between stations on the same continent.

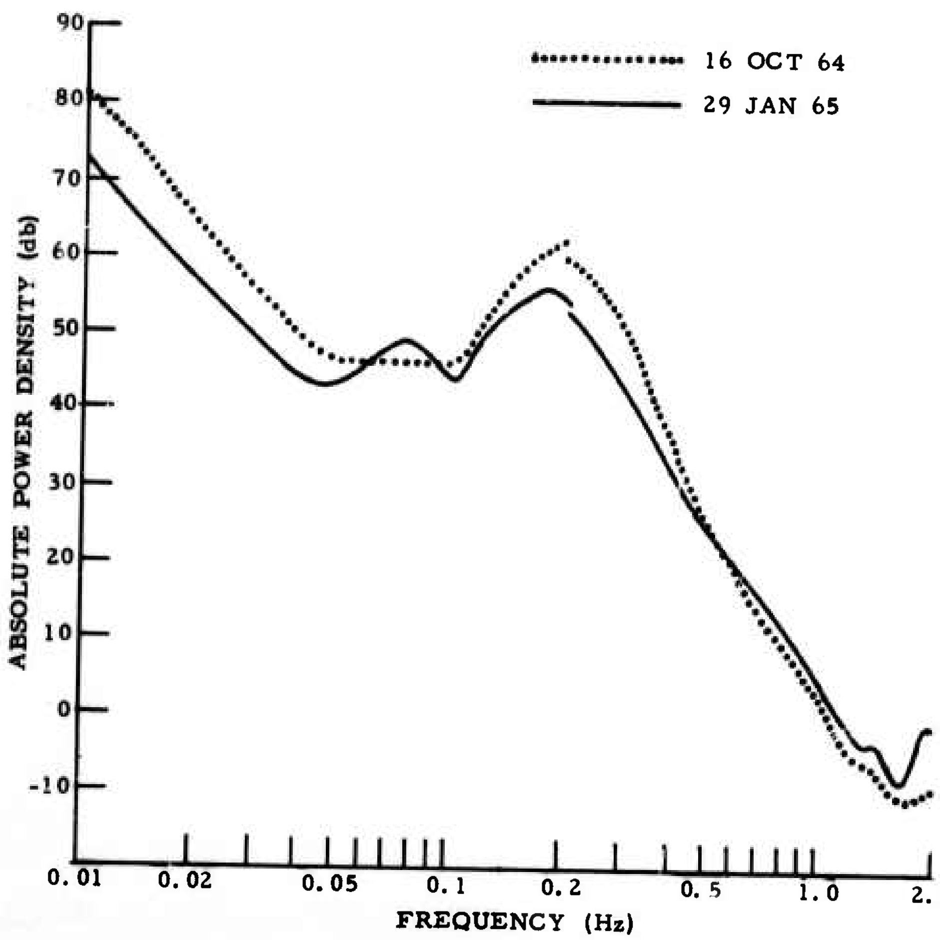

Figure II-4. Absolute Power-Density Spectra at CPO

A particular example is the coherence of 0.15 seen at 0.26 Hz between TFO and RKON. It may be significant that this, the highest observed coherence, occurs for two stations lying on a great circle passing through an intense storm off the coast of Newfoundland. Wavenumber analysis at TFO indicates trapped-mode energy with phase velocity of approximately 3 km/sec from the Newfoundland direction; it appears possible, therefore, that this peak represents valid seismic coherence between widely separated stations for directional trapped-mode energy. There is the possibility, however, that the coherence is instrument-related.

The spatial organization of station noise fields at CPO, TFO, NPNT, OONW, and GGGR is examined using high-resolution wavenumber spectra for two noise samples from days of strong storm activity. Also, K-line spectra are computed for the crossarrays at OONW, GGGR, and NPNT. Array dimensions generally limit analysis to frequencies below 1.0 Hz. A discussion of the procedure and a description of an experiment conducted to establish the validity of such noise spectra are presented in Advanced Array Research Special Report No. 8.[2]

Analysis of these spectra reveals a strong dominance of directional trapped-mode surface-wave energy at all stations except TFO (and, to a lesser extent, NPNT) where directional bodywave noise dominates above 0.3 Hz. The trapped-mode energy appears to be generated primarily by surf action related to regional meteorological activity. Similarly, much of the TFO bodywave noise appears storm-related.

Good agreement between 2-dimensional and K-line wavenumber spectra is obtained, considering the differences in smoothing and resolution. The 2-dimensional wavenumber spectra are computed from spectra obtained by Fourier-transforming over a 409.6-sec data gate, yielding a frequency resolution of 0.0025 Hz. The K-line spectra are Danielle-smoothed over 41 points for a 0.1-Hz resolution. Only four seismometers along each arm are available for the K-line estimates.

Figure II-5 shows high-resolution wavenumber spectra computed at 0.2, 0.4, 0.6, and 0.8 Hz at OONW. Spectral peaks occur in the direction from which the energy arrives. Relative peak power levels shown on each plot illustrate the wide dynamic range examined.

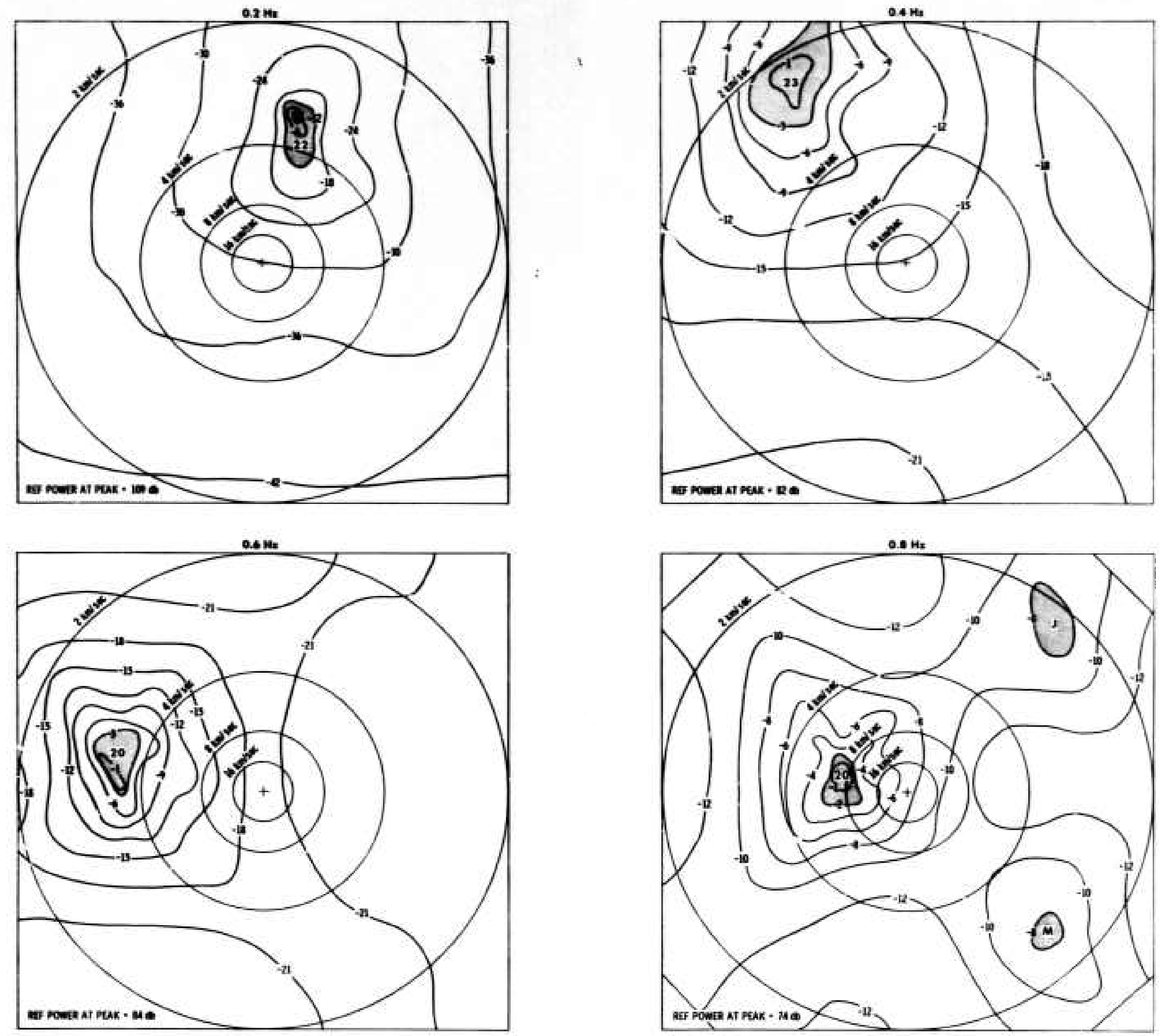

Figure II-5. High-Resolution Frequency-Wavenumber Spectra at OONW: 29 January 1965 Noise Sample

Figure II-6 shows K-line spectra at the same frequencies for each arm of the array. Integrated wavenumber power-density functions are superimposed on each plot. The dashed lines represent apparent horizontal velocities of 8, 3, and 2 km/sec. Positive wavenumber corresponds to propagation from north to south. Due to normalization procedures, power-level differences between frequencies are not reflected in the vertical scales shown; however, some smearing of the dominant 0.2-Hz power through the spectral window has likely occurred. Related peaks on the K-line and 2-dimensional spectra are numbered and refer to storms indicated on the surface weather map, Figure II-7.

The dominance of regional storm energy at each station suggests that storm-tracking could be performed by the network. In a sense, this is true; however, results indicate that energy from storms is observed by the various stations at differing frequencies, velocities, and propagation modes. Differing travel paths, distances, earth filtering, and nonisotropic radiation patterns could explain this observation. Therefore, network storm-tracking using stations limited by trapped-mode energy does not appear particularly promising. For the same reasons, the lack of noise coherence at the network level rules out useful application of multichannel filtering techniques to noise suppression. The lack of coherence and the highly variable station noise levels indicate that delay and sum procedures, coupled with weightings based on signal-to-noise ratios, will provide optimum signal extraction at the network level if signal distortion is not found to be a problem.

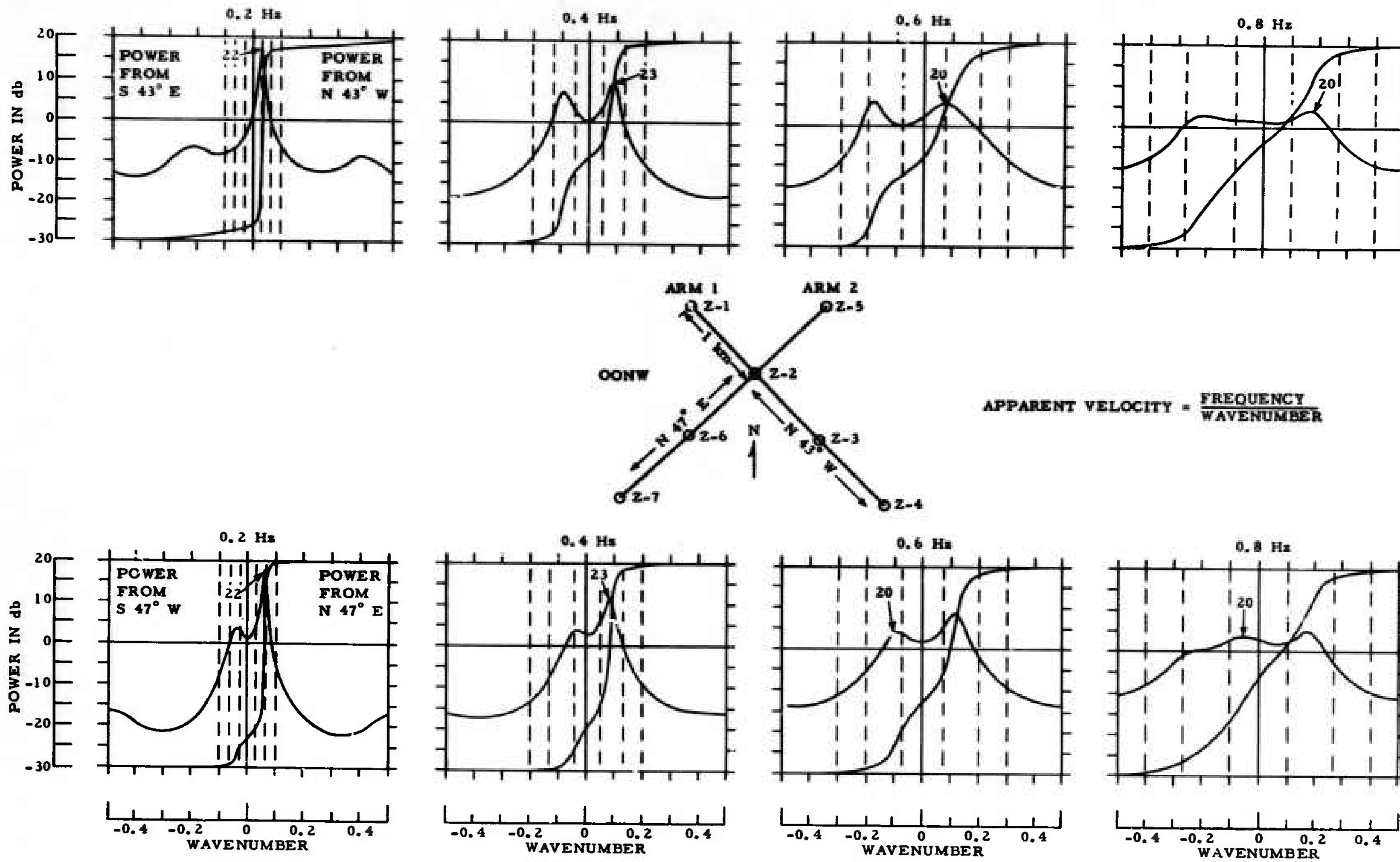

Figure II-6. K-Line Wavenumber Spectra at OONW: 29 January 1965 Noise Sample

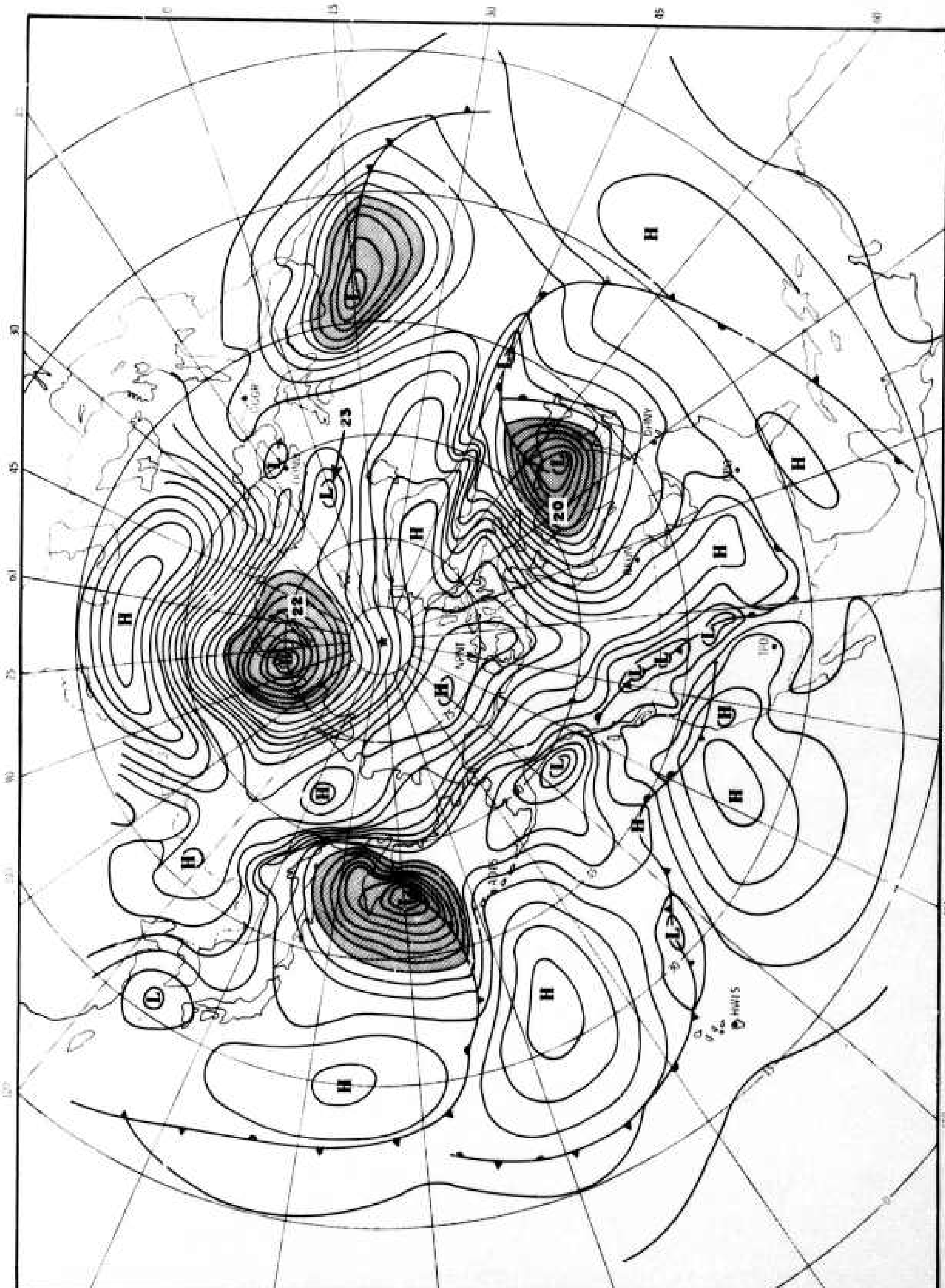

Figure II-7. Surface Weather Map for Northern Hemisphere: 29 January 1965 at 0600 GMT

B. NETWORK SIGNAL CHARACTERISTICS AND COHERENT PROCESSING

Study objectives include characterizing seismic signals at the network level and examining methods to exploit these characteristics for detection and classification of seismic events.

A primary study area is the similarity of the network-recorded signal. The investigation also includes several network signal-extraction and phase-detection techniques and signal-location and separation methods.

To evaluate the network's effectiveness, four experiments have been performed. These experiments and their objectives are as follows.

- Depth-Phase Extraction

  This study investigates the ability of various network processing techniques to enhance depth phases.

- Signal Separation

  This experiment investigates the ability of network processing to recognize the condition of a simple event obscured by a complex event and to locate and separate the two.

- P-Coda Enhancement

  This study determines the relative merits of various signal processing methods at the network level and the effect of network processing on background noise, primary P-wave signals, and P coda.

- Evaluation of a Worldwide Coherent Energy Analysis Technique

  This study presents one simple method for real-time network processing and data presentation and analyzes several problems which will be encountered in real-time network processing.

1. Depth-Phase Extraction

Four events are processed to investigate the depth-phase enhancement capability of network processing.

One technique consists of time-shifting and summing the visually aligned station outputs after squaring and integrating each. Time shifts are based on pP-P arrival-time differences according to USC&GS focal-depth estimates.

Another evaluated technique involves the use of a matched-filter output (P-30 correlation) resulting from crosscorrelation of the initial P wavelet with the entire P coda. The P-30 correlations and their squared and integrated counterparts are time-shifted and summed according to pP-P intervals.

In general, the network processing techniques obtain consistent indications of depth phases. Depth phases are equally or more evident on some station recordings, but several stations do not indicate detection. Network processing, therefore, would produce reliable event classification in terms of detection and identification of depth phases. Other automatic pP-detection network processing techniques probably could improve this reliability if the station records were weighted in some fashion, since evidence of pP is stronger on some station records than on the network output.

2. Signal Separation

The signal-separation study is performed to determine the ability of a limited network to separate time-overlapping events using a square-law output from beamsteered traces. The technique is useful for monitoring small areas of interest and would be particularly effective for detecting weak events such as explosions, which are masked by stronger regional events.

Several cases have been evaluated: a single event; simultaneous recording of a simple and a complex event, both of the same magnitude with epicenters 1° apart; a similar case with the simple event reduced one-half unit in magnitude; a simple event occurring 10 sec after a complex event having the same magnitude and 1° away; and a similar case with the simple event again reduced one-half unit in magnitude. In all cases, visual time alignment compensates for time residuals.

For each case, 25 beamsteers are formed — one for each intersection of a 0.5° grid for a 2°-x-2° coverage. Square-law outputs at five different times are contoured over the grid.

Figure II-8 presents five beamsteer plots showing resolution of two equal-magnitude events occurring 1° apart and separated in time by 10 sec. Plot 1 corresponds to a time preceding both events. Plot 2 shows detection and location of the first, more complex event. Plot 3 shows declining energy from this event, while plot 4 shows that the second event has been detected and located. Plot 5 indicates no further energy release from the epicenter of the second (simple) event, while energy from the first event is still available.

Results of the experiment show that a limited 8-station network can successfully separate two time-overlapping events, even if magnitude differences are only one-half magnitude and even if epicenter separations are as little as 1°. With an increase in network coverage (more stations), events with larger magnitude differences and/or less epicenter separation could probably be individually detected, located, and sufficiently well-separated for correct source-type identification. The time-residual effect on this capability for event resolution should be evaluated.

3. Signal Enhancement

Since good estimates of P-wave spectral content and P-coda complexity are extremely valuable in event classification, the ability of a network to provide improved P-coda estimates also is investigated.

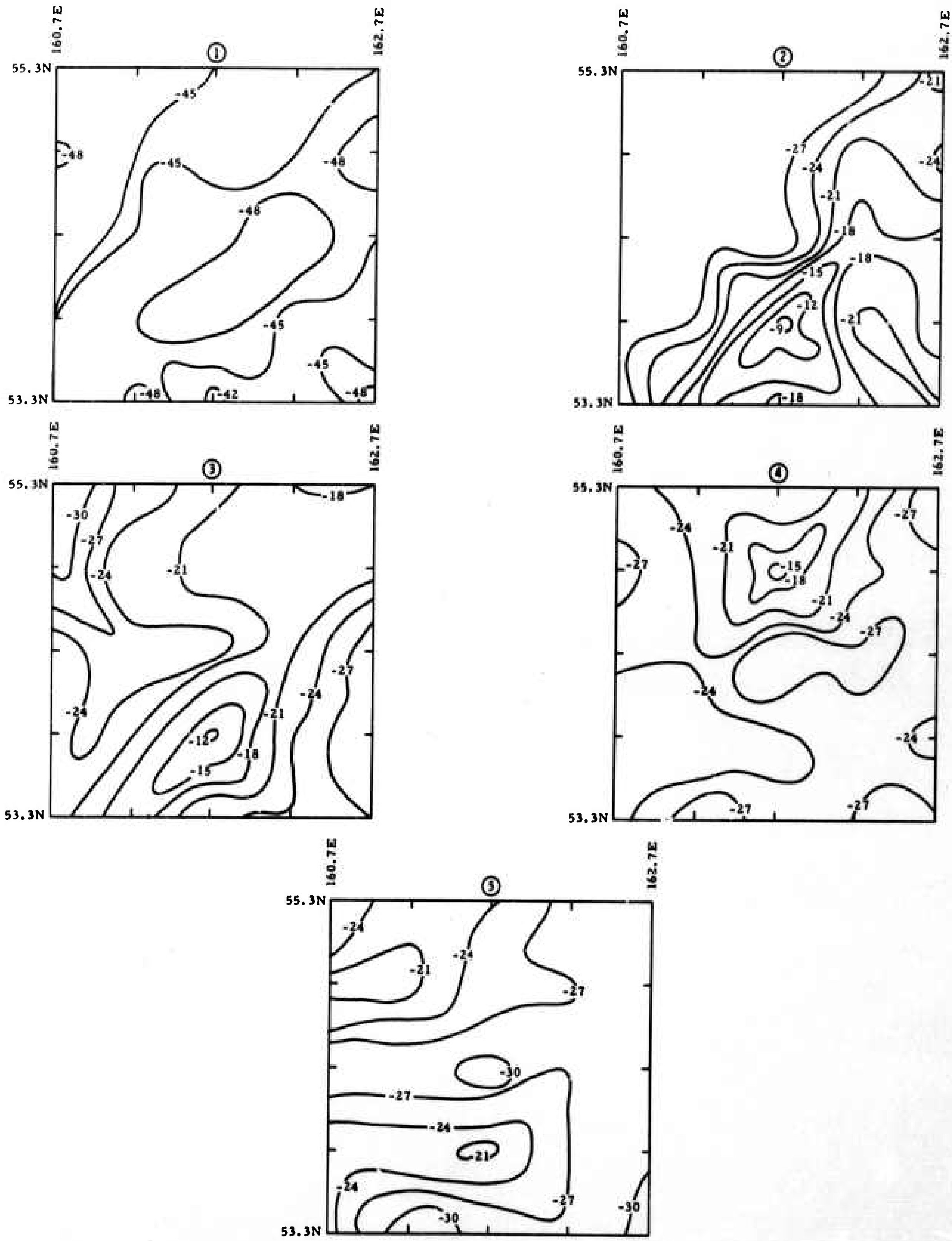

Figure II-8. Simulated 8-Station Recording of Two 5.8-Magnitude Earthquakes Separated 10 sec in Time and 1° in Space

Two earthquakes are processed to determine the extent of the short-period P-wave similarity problem and the relative merits of simple beamsteering, weighted beamsteering, and beamsteering of Levinson-equalized data. The effects of each on P wave, P coda, noise reduction, and apparent event complexity are examined through peak-signal-to-rms-noise measurements and broadband SNR improvement vs frequency. Eight stations are represented in the network signal analysis, and all station outputs are bandlimited (0.8- to 2.8-Hz zero-phase filter) prior to network analysis.

Large dissimilarities in signal waveform and SNR are observed across the network for the two events. For example, the relatively simple Kamchatka event reflects interstation correlation coefficients ranging from 0.52 to 0.96. Specific Levinson equalization filters designed for each event work well for the Kamchatka event but only moderately well for the more complex Kurile Islands event. Poorest equalization usually occurs for stations with low SNR's. This suggests that, in the absence of well-equalized network data, beamsteering using weights proportional to station SNR would be an effective approach, because stations with better signal estimates would exert greater influence on the network sum. This proves to be the case. Weighted beamsteers yield higher SNR's than beamsteers of either unweighted or equalized data. Results indicate that SNR improvements with Levinson-equalized traces are probably not sufficient to warrant the additional processing complexity at the network level. Beamsteers are formed through visual signal alignments; thus, the effects of station time residuals are not considered.

Autocorrelations of station outputs are averaged and then used to compute average station spectra. Compared to these average spectra, spectra of the simple beamsteer of network data produce the following:

- Signal loss averaging 3 db at the peak signal frequency
- Broadband reduction in noise power of 9 db with eight stations
- SNR improvements of 7 to 13 db within the signal band
- Significant attenuation of energy in the P-coda interval (7 to 9 db), indicating that the majority of this energy is noise or scattered signal rather than aftershocks or depth phases

Weighted beamsteers provide a minimum of 4 to 7 db additional improvement at frequencies of peak signal energy density and even larger improvements at other frequencies within the signal band.

These results show that signals can be enhanced effectively at the network level by simple beamsteering and that SNR weighted beamsteering is an excellent technique for signal enhancement. Event classification should be aided by network processing, since estimates of signal complexity are improved by reduction of scattered signal energy in the P coda.

Another signal-enhancement experiment, although only indirectly related to network processing, was performed to test the ability to detect and locate a very weak teleseism through high-resolution frequency-wavenumber spectra.[4] The experiment demonstrated that this technique, applied to a single-array station, could provide the preliminary location precision required before network processing.

4. Worldwide Coherent Energy Analysis

The continuous worldwide monitoring of both transient and steady-state seismic energy sources would be highly desirable if physically meaningful and easily interpretable displays were provided. Only such a worldwide network can provide the information necessary to permit such coverage. Many different computational methods are possible for combining the outputs from all network stations to obtain such displays. This study evaluates a simple technique for such displays and a simple technique for such network processing.

The technique, essentially a beamsteer in the frequency domain, provides an estimate of P-wave power density as a function of the geographical location of its source. The technique can correctly locate equalized short- and long-period signals. Time anomalies do not appreciably affect event location with long-period data but, as expected, make the technique impractical for short-period data. For nonequalized signals and multiple events, the presence of sidelobes in the spectrum prevents correct event location; however, further study is indicated with similar techniques, since this simple technique does not use all available information and is overly sensitive to time anomalies. The experiment has shown that network data can be processed in real-time to produce a visual presentation suitable for monitoring any area of seismic interest.

In summary, network signal processing is shown to be feasible and particularly advantageous for certain signal-classification areas. Additional investigations of network signal processing are warranted and should be performed using larger amounts of data. Future experiments should use both explosion and earthquake data to produce quantitative measurements for event-classification experiments.

C. CHARACTERIZATION OF THE ARRAY STATION AS AN ELEMENT OF A NETWORK

Network studies are necessarily preliminary due to limitations of the network and data. Only a few signals, all from one general area, are examined at the network level. Similarly, analyzed ambient noise data do not represent conditions of year-round network operation. General characterizations, therefore, must be tentative. The concepts of network operation presented are consistent with available knowledge but must be recognized as preliminary in nature and subject to further investigation.

Preceding discussions have examined characteristics of seismic signals and noise observed at the network level. A fundamental understanding of these characteristics is important for proper exploitation of the network for detection and classification of seismic events. The role of the individual station as an input to the network also becomes more apparent through examination of these characteristics. This section attempts to define the array stations' contribution to coherent network processing. However, it is necessary to first consider some of the more important requirements of a functional network processing system.

1. Why a Network

The reasons for using network data for seismic-event discrimination are not necessarily obvious. Seismic arrays yielding high-quality data have significantly advanced the VELA UNIFORM program in terms of improved signal detection and source location. However, the network concept should provide surveillance capability superior to that obtained with any particular high-quality station, since problems of station variation in sensitivity with azimuth, epicentral distance, frequency content, etc., become less critical with multidirectional coverage of events. Similarly, event radiation patterns do not pose potential difficulties; in fact, the network can effectively utilize these patterns as an aid in event classification.

Considerable network data are used at present — primarily in terms of the off-line manual selection of useful information from a variety of station inputs. Off-line interpretation and collation of seismic information from stations all over the world through USC&GS result in periodic listings of seismic activity. A multitude of information appears to be already available. In fact, the large quantities of seismic data to be analyzed form a most cogent argument for network processing. As improvements are achieved in recording and analysis techniques, detection thresholds are lowered, resulting in exponentially increasing numbers of events for analysis.

Studies of worldwide seismicity[6] form a basis for projections of annual event occurrences ($m_b \geq 4.0$) approaching 10,000. This assumes worldwide station coverage sufficient to place stations within 20° of all plausible epicenters. Additional low-magnitude near-regional events would probably be reported by at least one station. Therefore, on a worldwide basis, events would probably be detected at a rate exceeding one event per hour. With increased proliferation of nuclear-weapon technology, more regions become suspect and require monitoring. Determination of clandestine testing must necessarily be done quickly and accurately. The only really plausible system for continuous on-line monitoring of seismic activity on a worldwide scale is an automated network.

Such a network should consist of a worldwide net of seismic-recording array stations in constant communication with a central interpretive and analytical facility. This central facility would be staffed by expert seismologists and technicians having access to visual on-line displays of seismic activity in areas of interest and being assisted by large-scale high-speed computing equipment capable of near real-time processing. The remote array stations would require a minimum staff, primarily for operational maintenance.

Thus, the advantages of network processing are many. Detection and analysis become virtually instantaneous through automated communication and processing. Since station analysis becomes unnecessary, required staffing of technically competent people becomes less of a problem. The central facility would provide to the seismologists a continuous evaluation of worldwide seismicity. Such a monitoring facility could conceivably provide earthquake or tsunami warning information based on analysis of shock activity, while continuing the primary surveillance task.

Combined analysis of many well-distributed stations should result in improved signal detection and source location. Event classification should be improved through better signal estimates and use of network discrimination statistics and network depth-phase detection and identification. Preliminary network studies performed during the current year under the Advanced Array Research program and discussed in other parts of this section indicate possible significant improvements in signal estimates (reduction in scattered signal), depth-phase discrimination, and signal-source location and event separation using rather limited networks. Studies of network discrimination statistics using a 5-station network also appear extremely promising.[7]

2. Array Station's Role in Such a Network

What, then, are the functions of the various elements that form the network, i.e., the array stations?

Obviously, a communications link (such as telemetry) must exist between each array station and the central facility. Automated predetection isotropic processing should be implemented at the array-station level, with continuous interrogation for events by some scheme such as square-law (square, integrate, and threshold) detection. Specific areas of interest within the range of the station would also be continuously monitored with directional array-processing techniques.

Upon detection of an event, information regarding arrival time, rough location, and possibly even signal waveform would be transmitted to the network facility.

Following event detection at one or more array stations, a request could be transmitted from the network to appropriate stations to implement postdetection processing, using refined timing and source-location estimates obtained at the network level from those stations initially reporting. Then, the stations would implement the designated (and automated) post-detection operations on the still-retained array data and resupply the network with refined information.

Isotropic preprocessing may fail to detect an event at a given station; however, subsequent directional processing at the command of the network (including the possibility of adaptive filters which could be quickly designed from measured noise preceding the network-predicted arrival time) could result in event detection. In a sense, the network would operate in an "adaptive" mode during event-detection periods, refining its estimates as additional information is acquired from the array stations.

3. Network Function

The function of the network facility is, in turn, to monitor incoming array-station outputs, implement network-level source-location and event-classification procedures, and provide various worldwide and regional displays for on-line visual monitors...

When event detection is reported by one or more array stations, the network, at the discretion of the seismologist who provides the necessary element of human judgment and control, may enter the "adaptive" operation mode and interrogate those array stations considered to be within range of the hypothesized epicenter. Obviously, although the network is operating in real-time, a built-in constant delay is required to allow for teleseismic traveltimes.

In addition to visual displays, the network facility would furnish estimates of event hypocenter, magnitude, and time, as well as classification as to type. Permanent records, such as filmed or taped recordings of seismic signals and the visual displays, would be acquired, as well as output listings of event activity (in a sense, a real-time automated bulletin).

Network signal and noise studies during the current year have indicated that network-level signal-extraction processing probably would consist of relatively simple procedures such as time-shift and sum (beamsteer) of station inputs after some form of station weighting. The apparently uncorrelated nature of the network noise field and the large variations observed for station rms noise levels with both geographic position and time suggest the need for some type of beamsteer weighting such as relative signal-to-noise ratios using a form that emphasizes the better stations. Estimates of signal complexity and energy-density distribution with frequency should improve through reductions in ambient noise and scattered signal with these procedures. Network-level processing complexity, therefore, does not appear prohibitive.

4. Desired Subarray Outputs to Network

Various types of subarray information would be applicable to network-level event detection, signal extraction, and phase identification; others probably would be more useful in event-classification procedures. Definitive work remains to be done in this area; however, previous and current-project VELA UNIFORM studies suggest certain useful inputs. Short-period vertical-component data, bandlimited and array-processed for isotropic coverage (or directional for specific areas of interest) currently appear most practical for P-wave detection — most likely by a square-law detection device. Planned studies of long-period 3-component array data may indicate feasible detection using surface waves; at present, however, long-period (and short-period horizontal-component) data appear most useful for postdetection procedures such as phase identification and event classification.

Subarray processors should be capable of furnishing several types of outputs. Most of these should be bandlimited to reduce the highly variable microseismic energy. Primary predetection processing should provide for isotropic P-wave signal extraction. Concurrent directional outputs monitoring specific areas of interest should also be included. A detection method such as square law is obviously needed. In addition, an output sensitive to low-magnitude regional events could prove useful for monitoring foreshock activity in the station area. Component rotation and vector resolution would be a required function for 3-component array data.

These outputs would serve primarily for station-level event detection. Some form of rough location information such as azimuth or epicenter should be available, as well as estimates of event magnitude and arrival time at the station. Upon detection, this information, probably along with the appropriate processor output, would be transmitted to the network. The transmission time of this information would likely be very short; continuous transmission from the subarray to the network would not be required.

Procedures for worldwide monitoring through visual displays probably would be practical only for long-period data (as indicated by current network studies).[1] Since long-period-data sampling rates are extremely low, an essentially continuous network display could be maintained by accumulating samples at the array station over some suitable period (such as an hour) and then transmitting all samples at a high transfer rate.

While network operation and the role of the subarray may appear rather complex, all of the various components are technically feasible at the present time. Current work with array processors has already indicated feasible implementation of all required operations. Many of the network operations are currently being simulated through off-line analysis of multistation information, and network implementation really means automation of these procedures in real-time. Such an operation, therefore, appears most feasible and necessary if worldwide surveillance is to be maintained.

D. CONCLUSIONS AND RECOMMENDATIONS

The detailed study of two samples of noise recorded simultaneously at five network array stations has revealed that the major contributor to short-period noise is storm activity which is at sea but is near a large landmass. Continent stations being affected by a particular storm record strong directional surface waves from the storm. These and other stations may or may not see bodywave energy from the storm. Since the ability to see bodywave energy from a storm seems to depend on the surface-wave noise level, it is reasonable to conclude that all stations receive some bodywave energy from such storms.

The frequency content of storm noise varies considerably from station to station — probably due to crustal filtering. Long-period noise does not appear coherent between stations — even those on the same continent. Except for stations afflicted by high cultural noise levels, the principal source of seismic-noise-field variation appears to be the variation in intensity and location of major storm centers.

These conclusions are based on the investigation of only a few noise samples, which were recorded by a rather limited network during periods of strong storm activity; accordingly, they should be regarded as tentative. More simultaneous noise samples, with some recorded during times of minimal storm activity, should be studied and, where possible, more array stations should be included in the network. Velocity filtering of array data should be performed to eliminate all except teleseismic bodywave noise in order to reveal the characteristics of the bodywave component. Although coherence between stations could be expected for bodywave noise only in the sense of some correlation as to source region and intensity vs time, these gross similarities might be useful in network processing.

Long-period noise should be examined, using a network of all available long-period array stations. A network of LP stations should provide greatly improved estimates of relative bodywave and surface-wave energy release for a given seismic event. An understanding of not only the LP noise characteristics at each station but the relation between stations in these characteristics would permit the specification of appropriate array and network LP data processing procedures.

Studies of short-period network recordings of several teleseismic events have indicated large variations in signal amplitude, frequency content, P-coda complexity, and depth-phase detectability. Less variation in the initial P wavelet (first 2 sec) has been observed, with the result that simple time-shift-and-summation network processing produces an improvement in peak-signal-to-rms-noise ratio (SNR) relative to the average station SNR. Similar reductions in P-coda energy indicate that network processing can provide improved estimates of event complexity. Weighting station outputs by their SNR prior to network beamforming provides significantly more

SNR improvement than simple beamforming. A study of a limited network's ability to resolve and to locate two events closely overlapping in time and space has indicated that a resolution of better than 1° can be achieved if time anomaly compensation can be provided.

The study of network signal characteristics has also been very limited as to the number and variety of signals examined and as to the extent and quality of the network. A continuation of the network signal characteristics and processing study, using more signals recorded with a larger network, is recommended. Signals should be obtained for explosion events as well as earthquakes representing a greater variety of depths, magnitudes, and source regions. The effects of using source-region average time anomalies for network beamforming should be investigated.

Other approaches to enhancement and automatic detection of depth phases should be considered. Long-period signal data should be included to determine the effectiveness of network discrimination criteria based on surface-wave measurements. Both LP surface-wave and SP bodywave radiation patterns and relative bodywave-to-surface-wave energy should provide good discrimination. Methods for continuous network processing for automatic event detection and location are feasible and should be developed.

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SECTION III

MULTIELEMENT SYSTEM STUDIES

A. THEORETICAL CROSSPOWER AND CROSSCORRELATION BETWEEN SEISMOMETER OUTPUTS

Conventional design of Wiener multichannel filters for seismic arrays requires knowledge of the crosscorrelations between sensor outputs if the design is to be in the time domain or knowledge of the crosspower spectra if the design is to be in the frequency domain. Noise statistics are frequently obtained by recording a noise sample of adequate duration and using these data to estimate the appropriate quantity. In the case of signals which may have short durations, it is generally difficult to obtain reliable statistical characterization in this way. An alternative is to intuitively model the signal in frequency-wavenumber space and calculate the cross-correlations or crosspower spectra corresponding to the model. In some circumstances, this theoretical approach is also valuable for generating the noise statistics.

The goal of this work was to develop a computer program providing the desired crosspower spectra corresponding to standard frequency-wavenumber space models. If crosscorrelations were desired, these would be obtained in the program by discrete Fourier-transforming of the crosspower spectra.

At the time this work was begun, a program had already been written to compute the crosspower between two vertical-displacement sensors located on the surface for either the disk or the annulus models. The initial intent was to generalize this program to include all situations of interest such as multicomponent sensors, sensors which measure quantities other than displacement, sensors at various depths, and dispersive modes of propagation. It soon became evident, however, that this approach would result in a complex and unwieldy program. A better approach was to begin with a general treatment covering all situations of interest, because each is merely a specific aspect of the same problem. Then, the solution for any given case could be obtained in a unified manner.

The theoretical basis for the program was developed. Before implementation of the program, however, consideration of priorities dictated that this work be discontinued. The theoretical results are presented in Array Research Special Report No. 5.[8] A brief discussion of the technique is given here.

First, compressional- or Rayleigh-wave propagation is considered. The vertical displacement at a point on the free surface is characterized by selecting an appropriate model for its power distribution in frequency-wavenumber (f-$\vec{k}$) space. The assumptions are that the propagating medium can be modeled satisfactorily by a series of horizontally stratified homogeneous layers overlying a homogeneous halfspace and that such a model has been defined. The problem is to determine the cross-power spectrum between the horizontal and/or vertical displacements at two points within the medium.

Let the f-$\vec{k}$ space model for vertical displacement on the free surface be $\Phi_{ss}(f, \vec{k})$. Two such models are used. These are chosen to represent as closely as possible typical plane-wave seismic propagation and to make ensuing calculations tractable.

The first model represents the isotropic case where energy is equally likely to be coming from any azimuth. At any frequency, the absolute values of the wavenumber where energy occurs can have just one specific value. In cylindrical coordinates, this model can be expressed as follows:

$$\Phi_{ssI}(f,k,\theta) = \frac{P(f)}{2\pi k_1(f)} \delta\left[k - k_1(f)\right] ; \qquad 0 \le \theta\ 2\pi$$

where δ is the dirac function and $P(f)$ is the power density for free-surface vertical displacement. The function $k_1(f)$ defines the radius in $\vec{k}$ space where energy may exist at a particular frequency. An isotropic Rayleigh-wave mode is represented exactly by this model if $k_1(f)$ is the dispersion curve for that mode. The isotropic compressional wave is also represented exactly if the apparent speed has just one value V; in this case, $k_1(f) = f/V$. The more general case of compressional waves covering a range of speeds may necessitate combining a group of these models with properly chosen values of V.

The second model representing energy coming from the direction θ_1 is expressed as follows:

$$\Phi_{ssD}(f,k,\theta) = \frac{P(f)}{k_1(f)} \delta\left[k - k_1(f)\right] \delta\left[\theta - \theta_1\right]$$

The selection of one of these models and the model for the propagating medium implicitly specifies the relationships between displacements at two points in the medium. The Haskell matrix formulation is used to derive the specific nature of these relationships. To accomplish this, distinction between Rayleigh and compressional propagation is made by imposing conditions on the behavior in the halfspace. The matrix formulation leads to f-$\vec{k}$ space transfer functions $A_v(f, \vec{k})$ and $A_h(f, \vec{k})$ which relate vertical and horizontal displacement at the location of one sensor to the free-surface vertical displacement directly above. For example, in the Rayleigh-wave case, these functions relate the amplitude and phases of the free-surface vertical displacement to those of the subsurface-location vertical and horizontal displacements resulting from a single plane wave propagating with specific values of f and $\vec{k}$.

Similarly obtained are $B_v(f, \vec{k})$ and $B_h(f, \vec{k})$ which relate vertical and horizontal displacement at the location of the second sensor to free-surface vertical displacement directly above the first sensor location. $B_v(f, \vec{k})$ and $B_h(f, \vec{k})$ include a phase-shift factor to account for the azimuthal separation of the two displacement locations. These transfer functions are then combined with the model for free-surface vertical displacement to obtain the f-$\vec{k}$ space crosspower between displacements at the two sensor locations. The resultant expression is of the form

$$\Phi_{12}(f, \vec{k}) = \frac{B_i^*(f, \vec{k})}{A_j(f, \vec{k})} \Phi_{ss}(f, \vec{k})$$

where * denotes complex conjugate and where i and j are h or v, depending on the component of displacement under consideration.

This result corresponds to the following convention for the crosscorrelation function and crosspower density:

$$n_{12}(\tau) = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} n_1(t)\, n_2(t-\tau)\, dt$$

and

$$N_{12}(f) = \int_{-\infty}^{\infty} n_{12}(\tau)\, e^{-i2\pi f\tau}\, d\tau$$

The simple nature of the models $\Phi_{ss}(f, \vec{k})$ permits integration of this 3-dimensional crosspower over $\vec{k}$ space to obtain the desired 1-dimensional crosspower. The expressions for this quantity are given in the report and can be calculated at the various discrete frequencies.

Love-wave propagation is handled in essentially the same way. A difference results from the absence of vertical displacement for this type of wave. In this case, therefore, the models $\Phi_{ss}(f, \vec{k})$ represent the 3-dimensional autopower of a hypothetical surface sensor which measures horizontal displacement in all directions.

A second difference is that the matrices which occur in this development are 2 x 2, whereas those for the compressional or Rayleigh waves are 4 x 4. Aside from these differences, the development proceeds as just outlined.

As an example of the extension of these results to other situations, the modifications necessary to deal with strain measurements in a compressional-wave field are developed. The only modifications are shown to be slight changes in the $A_j(f, \vec{k})$ and $B_i(f, \vec{k})$.

In summary, a method for calculating the crosspower density between two sensor outputs corresponding to an assumed $f, \vec{k}$ space model has been outlined. Specific results are presented for displacement sensors in the presence of Rayleigh, Love, and compressional modes of propagation. The method is readily extendable to other cases of interest. As an example of this, the strain sensor relations have been derived.

B. EXTRACTION OF DIRECTIONAL SIGNAL FROM ISOTROPIC NOISE OF THE SAME SPEED

In considering methods of signal-extraction processing for planar arrays of long-period vertical seismometers, the ambient noise is found to have two distinguishing characteristics: bodywave noise, if present, represents a much smaller proportion of the long-period noise than it does in the frequency range of short-period instruments; and, at these low frequencies, the only significant mode of surface-wave propagation having a vertical component may be the fundamental Rayleigh wave.

The extraction of the Rayleigh phase of an event from such a noise field is a matter of considerable interest. This signal-extraction problem is somewhat unique because both the signal and the predominant noise energy travel with the same speed. This raises the question of the relative merits of time-shift-and-sum vs multichannel filter processing under these circumstances. A brief theoretical study of this problem has been performed; results are presented in Advanced Array Research Special Report No. 9.[9]

The case considered is that of a signal coming from a specific direction at a speed of 3 km/sec and having a white power-density spectrum for vertical displacement. The small amount of dispersion over the frequency range considered (0.0 to 0.25 Hz) is neglected, but its effects can be inferred by appropriately modifying the frequency scale of the results. The ambient noise is composed of both 3-km/sec organized noise resulting from an isotropic source distribution and random noise. The vertical displacement power-density spectra for both types of noise are white.

Considered are a 7-element array and a 19-element array, both arranged on a hexagonal grid with 20-km spacing between elements.

Theoretical signal-to-noise ratio (SNR) improvements for two types of processors are computed. The first of these aims the array at the signal by time-shifting and summing the seismometer outputs to reinforce the signal. The second is a multichannel filter designed to minimize the mean-square-error between its output and the signal. For the singular, directional signal used in this study, this second type of processor is a maximum SNR processor. In the presence of purely random noise, the MCF design procedure yields the beamsteer processor; i.e., the individual filters are simply phase shifts. In the presence of organized noise, however, the MCF capitalizes on the particular spatial organization of the noise and performs better than the beamsteer processor.

Results are obtained for varying proportions of organized and random noise. The three cases considered are for 1-percent, 4-percent, and 20-percent random noise. In the case of 100-percent random noise, both processors would yield $\sqrt{N}$ improvement in SNR.

Typical results are illustrated for the 7-element array in Figure III-1 which shows SNR improvements for both processors and for two signal directions. These curves are for the 1-percent random noise, 99-percent organized noise case. Qualitatively similar to these are the results for the other relative noise proportions and for the 19-element array.

The principal result is that, for this particular problem, MCF processing is significantly superior to beamsteer processing only at frequencies below 0.05 Hz where neither processor yields a $\sqrt{N}$ improvement in SNR. At frequencies above the 0.05 Hz, the improvement yielded by either processor oscillates appreciably about $\sqrt{N}$. The aliasing properties of the regularly spaced array cause this behavior. At any frequency, both

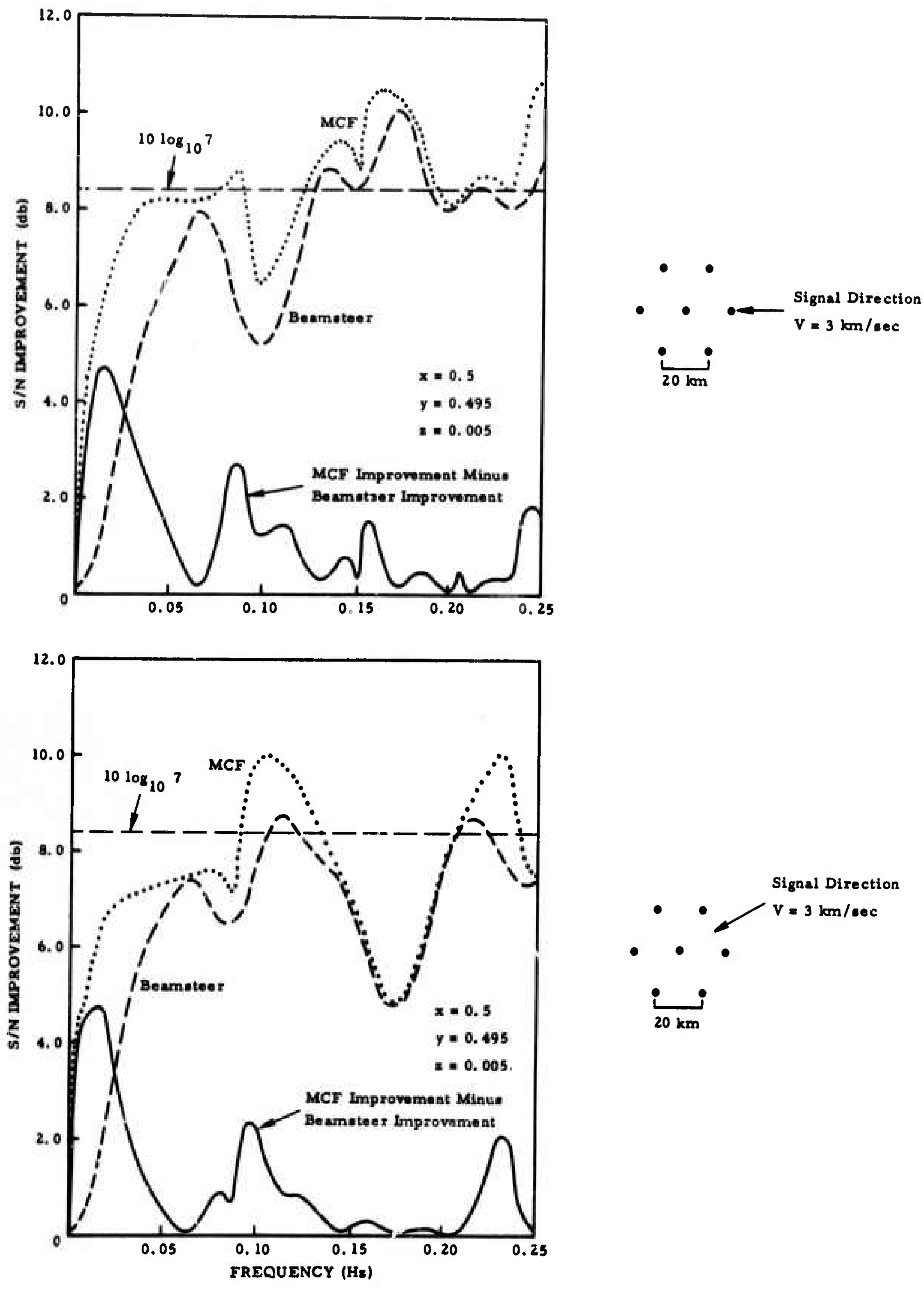

Figure III-1. SNR Improvement for 7-Element Array with 99:1 Organized-to-Random-Noise Ratio processors have high response to the wavenumber of the signal. At certain frequencies, some of the aliases of this high-response wavenumber coincide with portions of the organized noise. Here, the processors must pass more of the organized noise, and poor performance is observed. Comparison of the two sets of curves in Figure III-1 shows that the detailed nature of this behavior is markedly a function of the azimuth of the signal.

These substantial variations in SNR improvement, resulting from the array geometry, are a significant consideration in planning an array or understanding the performance of an existing array. The close agreement between computed improvement and that suggested by aliasing considerations is valuable. Considerations of the aliasing properties of an array, it appears, can lead to a quick estimate of array performance when the organized noise field is not purely isotropic.

C. ANALYSIS OF K-LINE WAVENUMBER SPECTRA FROM THREE WMO NOISE SAMPLES

To aid in the design and evaluation of an experiment involving an array of horizontal and vertical seismometers at WMO, three previously recorded noise samples from that station have been analyzed.[10]

The analysis uses 1-dimensional K-line wavenumber spectra. These are projections of 2-dimensional wavenumber spectra onto one dimension. The high-resolution of these K-line spectra permits a more detailed analysis of the WMO noise samples than was possible previously.

One-dimensional spectra are obtained for three directions parallel to the sides of the triangular array. These are computed for 20 frequencies from 0.2 to 3.0 Hz, with increments of 0.1 Hz from 0.2 Hz to 1.2 Hz and 0.2 Hz thereafter. Figure III-2 is an example of the wavenumber power-density spectra and integrated wavenumber power-density

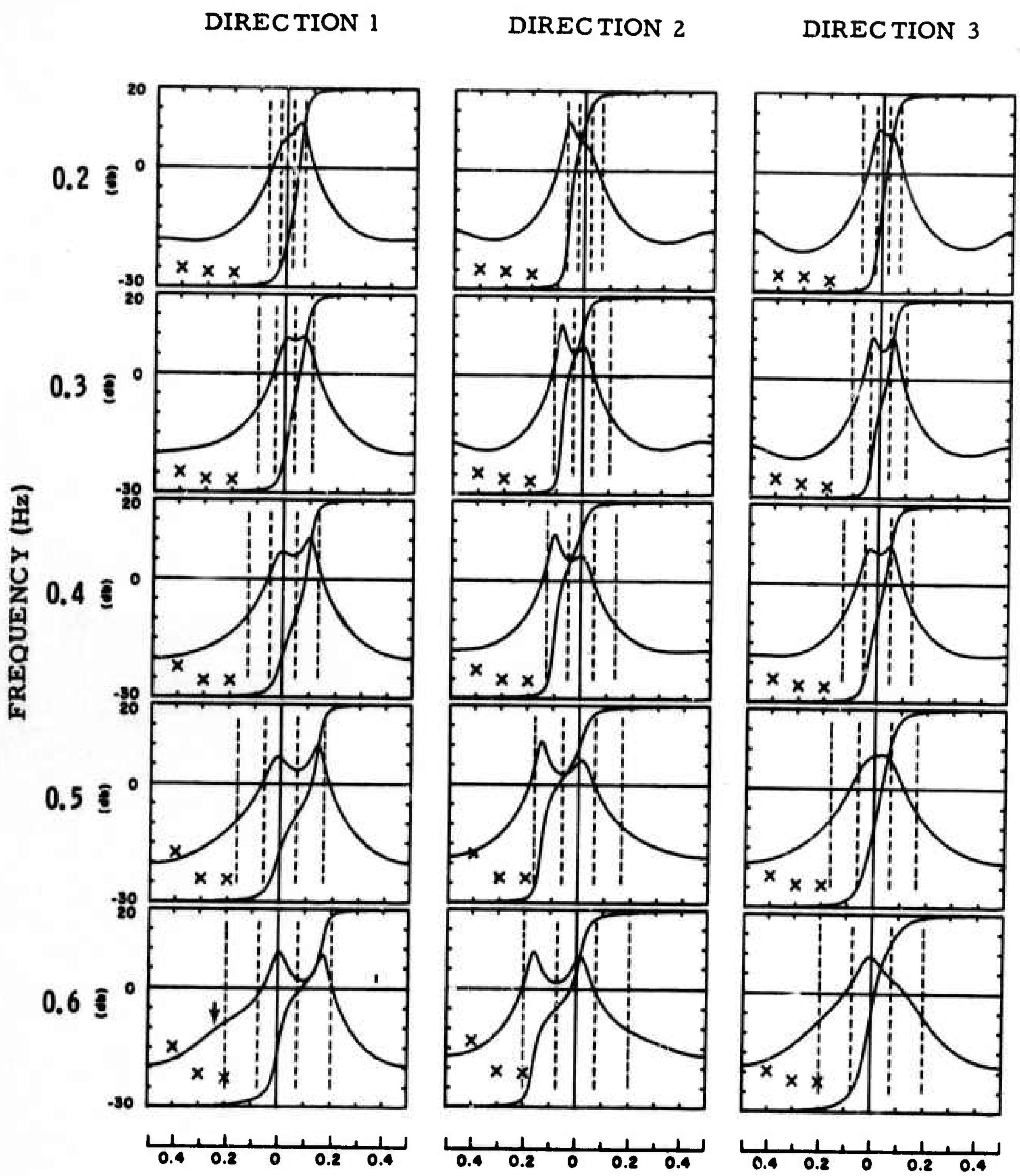

Figure III-2. Wavenumber and Integrated Spectra from WMO Noise Sample 1 functions computed from the first noise sample NS 1. For each wavenumber spectrum (power density plotted in db vs wavenumber in cycles/km), the 0-db level indicates the spectrum's average value. The solid vertical line at k = 0 represents infinite apparent velocity; i.e., the direction of wave propagation is perpendicular to the line of the seismometer array. Dashed lines on either side of this line show apparent velocities of 8 km/sec and 3 km/sec.

The normalized integrated wavenumber power-density function shown is

$$\int_{-K}^{k} P(k)\ dk$$

with

$$\int_{-K}^{K} P(k)\ dk = 1$$

where P(k) is the wavenumber power-density spectrum and K is the fold-over wavenumber. The foldover wavenumber is equal to 1 divided by twice the spacing between seismometers along each arm (in this case, 1 km).

The peaks appearing in these 1-dimensional spectra are not immediately interpretable, since they represent the projection of the true wavenumber locations of energy concentrations onto the three lines. The 2-dimensional location of a peak is determined by noting the apparent location of the peak along the three lines and using these apparent locations to triangulate. Clearly, two lines are adequate for this; the addition of the third line, however, provides an indication of the accuracy with which a peak has been located. When this is done, all three noise samples show a concentration of energy coming from the northeast, with a velocity ranging from 2.8 to 3.5 km/sec. In contrast with surface waves observed at other stations, this energy persists from 0.2 to 1.0 Hz. The broadband nature of this surface-wave energy suggests a near source. Two lakes located 5 to 8 km northeast of the center of the array seem likely to be generating this energy.

The other major component noted is bodywave noise (energy propagating with apparent velocities greater than 8 km/sec). Spectral resolution limited by the size of the array does not permit estimation of the velocity distribution for this noise.

In addition to the northeast Rayleigh wave and the bodywave components, some additional low-velocity noise is observed from 0.6 to 1.0 Hz. This noise component is probably isotropic Rayleigh-wave energy.

The percentage of the total power contributed by a specific component can be estimated using the integrated wavenumber power-density functions, again allowing for the fact that low-velocity energy may appear as high-velocity energy along lines perpendicular to the source direction. Then, if the total power-density spectrum is known, power-density spectra of the individual components can be determined. Figure III-3 shows these spectra for the third noise sample NS 3. Here, the individual components are estimated out to 1.0 Hz. Interference caused by the inhomogeneous geology of the area makes interpretation beyond this frequency difficult. Uncertainties in the calibration data, it is to be noted, make the absolute level of these spectra questionable. The relative levels, however, are considered accurate.

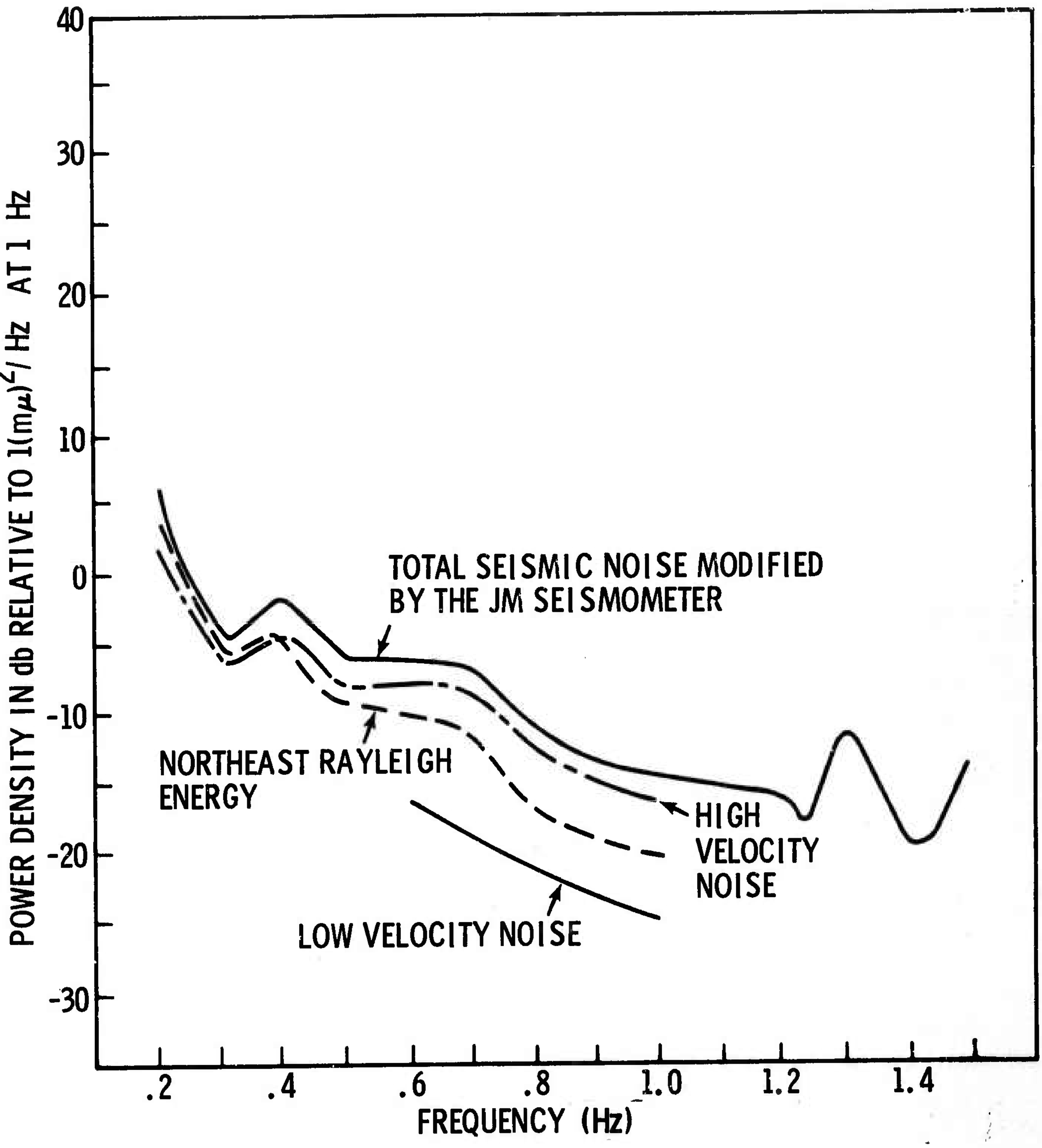

Figure III-3. Absolute Frequency Power Density Spectra for Three Noise Components in WMO Noise Sample 3

While most of the energy beyond 1.0 Hz is difficult to interpret, the 2.0-Hz line characteristic at WMO stands out clearly. Figure III-4 shows three possible triangulated locations of this energy for NS 1. The three locations result from the aliasing property of the array geometry. All three have possible surface-wave velocities which preclude determination of the true source direction without additional information. Results from the other two noise samples are almost perfect overlays of this figure.

D. P-WAVE SIGNAL EXTRACTION WITH ARRAY OF VERTICAL AND HORIZONTAL SEISMOMETERS

Recent theoretical studies show that arrays consisting of rings of radially oriented horizontal seismometers concentric with a central vertical seismometer can extract vertically arriving P-wave signals from Rayleigh-wave background noise.[11,12] This is accomplished by designing multichannel filters which use the Rayleigh component appearing on the vertical seismometer. This predicted value is subtracted from the vertical, leaving the P-wave signal which does not appear on the horizontals.

Installed at WMO during the second half of 1967 was an experimental array of this type, consisting of a central vertical seismometer and two rings of six horizontal seismometers with ring diameters of 1.15 km and 2 km. Data from this array have been processed in an effort to experimentally verify the theoretical conclusions.[13]

The analysis used PKP phases of two events and a ~~2.0~~ 20-min noise sample immediately preceding the second of these events; these were labeled SSA, SSB, and NSB, respectively. Before multichannel filters were designed, the data were antialias-filtered, decimated to a folding frequency of 2.98 Hz, and whitened.

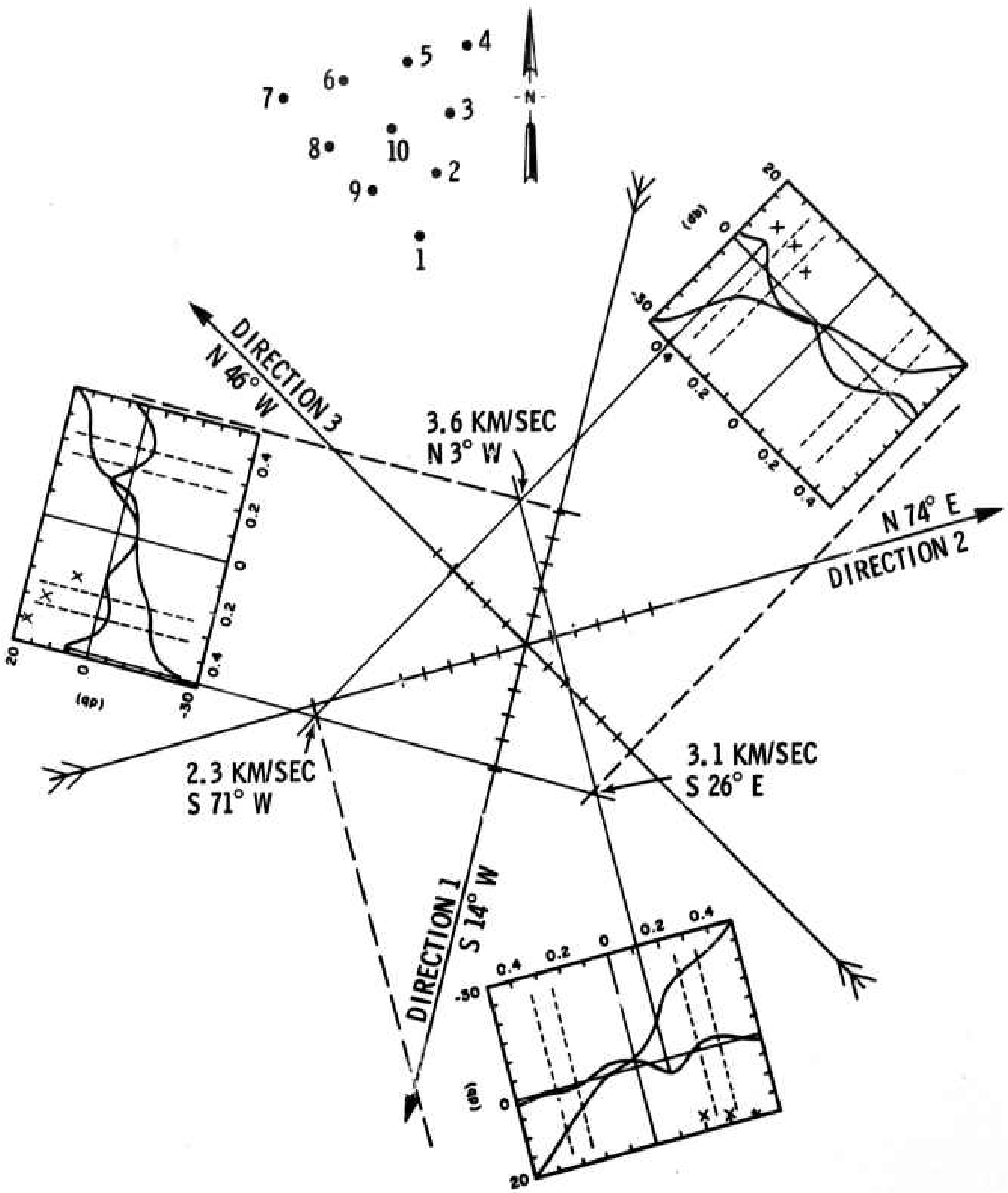

Figure III-4. Possible Directions and Velocities of 2.0 Hz Peak in Noise Sample 1

Two signal-enhancement processors were designed and applied to the data. The first was a conventional Wiener infinite-velocity signal-extraction filter. The noise correlation matrix was obtained from the 20-min NSB. The infinite-velocity signal (appearing only on the vertical seismometer) was assumed to have the same spectrum as the noise with an SNR of 4. The second processor, an adaptively designed prediction-error filter, used the horizontal traces to predict the noise off the vertical trace.[14] The filter was trained on NSB and then applied in the adaptive mode to NSB and both signal samples. In passing through the signals, the prediction error becomes very large. To prevent this error from disturbing the filters, the adaptation was suppressed at any iteration where the square of the error exceeded a selected multiple of the average square value of the data used in that iteration.

Figure III-5 shows spectra of the unfiltered vertical seismometer, the Wiener filter output, and the adaptive prediction error for NSB. Neither filter provides significant suppression of the background noise on the vertical seismometer. Spectra of the filtered signals show that the Wiener filter attenuates signals by about 2 db. The net result is that both filters provide about 2-db SNR improvement over the frequency range 0.0 to 3.0 Hz. This poor performance is not surprising below 1.0 Hz where the noise field is known to be dominated by bodywave noise which cannot be effectively suppressed by this type of array. At higher frequencies, however, better performance is to be expected.

Examination of the horizontal seismometer noise traces shows a great deal of nonuniformity from trace to trace and along a given trace. This suggests that these records are seriously contaminated by random nonseismic noise. Random noise seriously degrades the enhancement capability of this type of array. This appears to be the reason for the wide disparity between theoretical results and the experimentally obtained results.

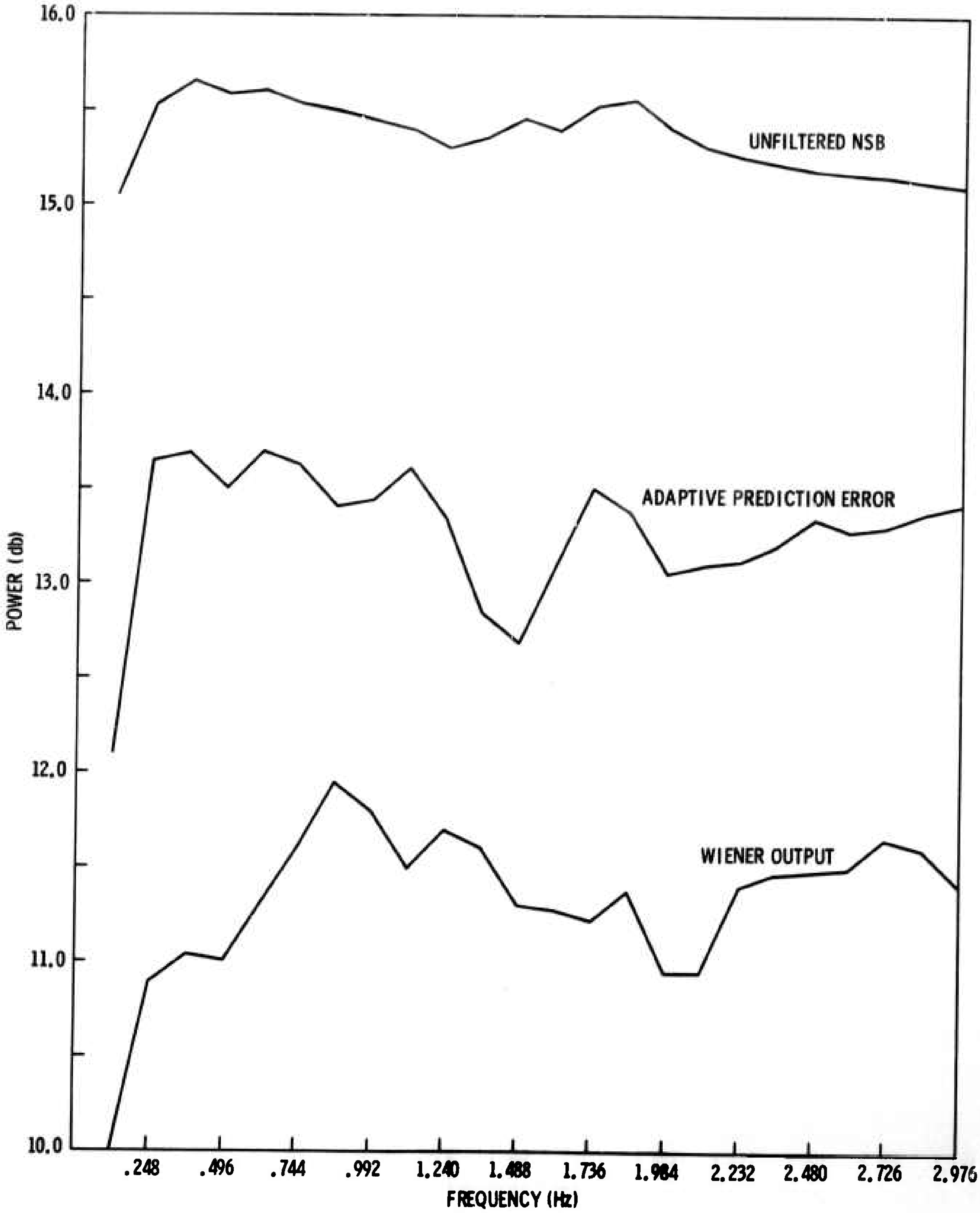

Figure III-5. Power Spectra of Filtered and Unfiltered Noise Sample B

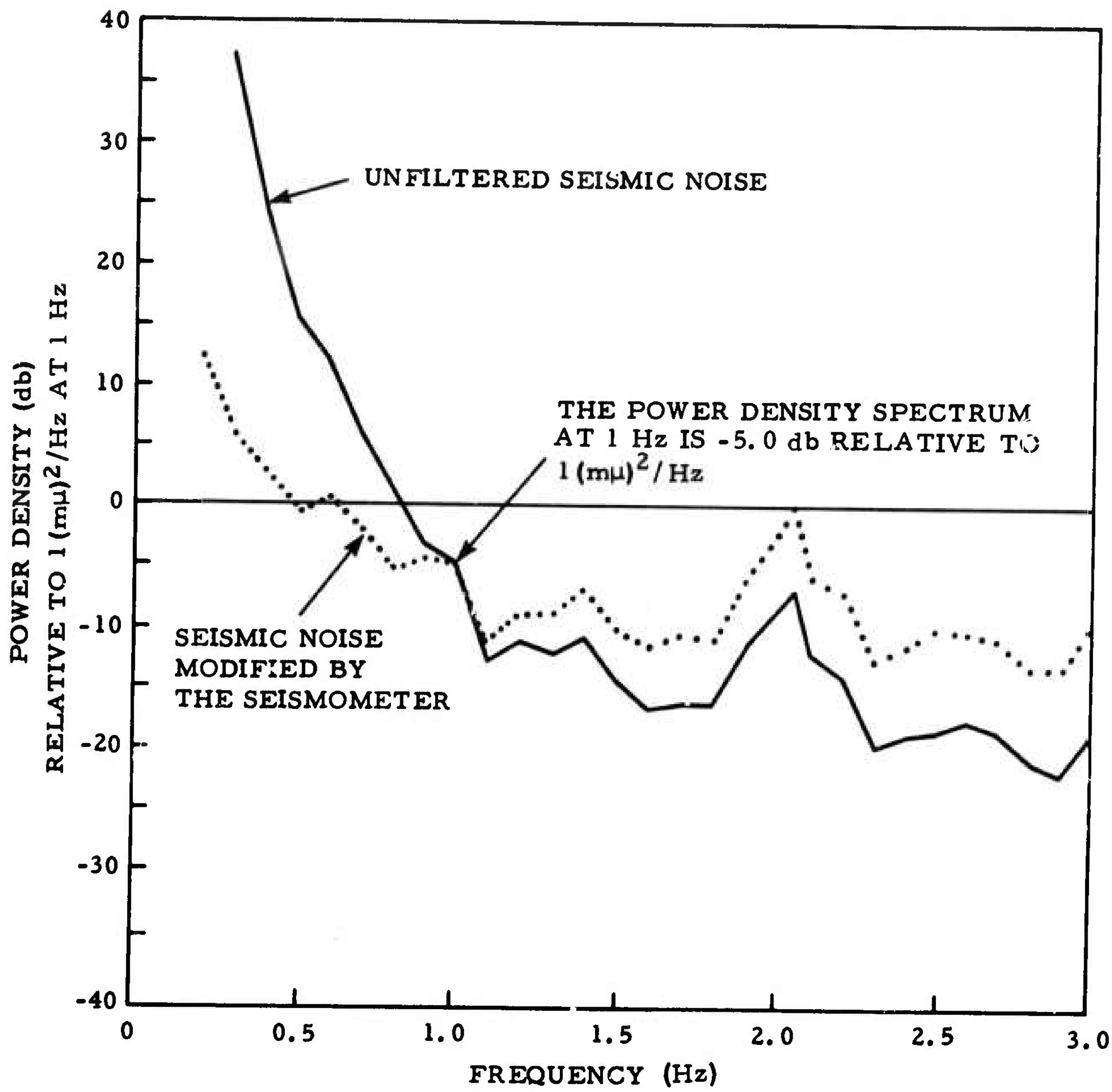

Figure III-6. Power-Density Spectrum of Ambient Noise at WMO

A previous report presented an absolute spectrum of WMO vertical seismometer noise,[10] mentioning that uncertainties in the calibration data make the absolute level of that spectrum questionable. Figure III-6 shows a spectrum obtained from seismometer U3, an element of the permanent shallow-buried array at WMO, on 5 October 1967 between 1700 and 1800 hr GMT. While the horizontal seismometer data recorded at this time are somewhat suspect, there is no reason to believe that the shallow-buried array was not functioning properly. Therefore, the spectrum presented here is considered to be a valid representation of the WMO ambient noise.

E. CONCLUSIONS AND RECOMMENDATIONS

A generalized procedure for the computation of theoretical crosspowers or crosscorrelations between the outputs of two seismic sensors has been outlined. The calculations are based on a layered propagating medium and assumed frequency-wavenumber models for the propagating energy. A computer program incorporating this theory would provide the theoretical noise and/or signal statistics used in the design of multichannel filters for multicomponent arrays.

A theoretical comparison has been made between beamsteer and multichannel filter processors for the extraction of a directional signal from isotropic noise. Both the signal and noise were assumed to propagate with the same speed. Considered were 7- and 19-element vertical seismometer arrays on hexagonal grids. MCF processing, while always superior, was found to be significantly better only at very low frequencies where neither processor achieved $\sqrt{N}$ SNR improvement. The aliasing properties of the arrays are clearly interpretable and significant at higher frequencies where SNR improvement oscillated about $\sqrt{N}$.

Computation of K-line wavenumber spectra from three WMO noise samples has provided new information concerning the ambient noise field. The presence of broadband surface-wave energy (0.2 to 1.0 Hz) coming from the northeast implies a near source (probably two lakes a few kilometers away in that direction). Also found to be appreciable in this frequency range is mantle P-wave energy (apparent velocity greater than 8 km/sec). The velocity of the 2.0-Hz energy, characteristic at WMO, was determined very precisely down to the ambiguity imposed by the aliasing properties of the array. Analysis of horizontal-vertical seismometer data recently recorded at WMO should be useful for resolving this ambiguity.

These recently recorded data have been analyzed to verify theoretical indications that arrays of vertical and horizontal seismometers are useful for extracting P-wave signals from ambient noise. Results obtained to date are inconclusive, possibly due to a high level of incoherent noise on the horizontals. Thus far, a 30-min noise sample relatively free of this contamination has not been used. A detailed analysis of these data is recommended in order to obtain a better experimental evaluation of this type of array.

SECTION IV

ADAPTIVE SYSTEMS STUDIES

A. HISTORY OF PREVIOUS WORK AND TASK OBJECTIVES

Procedures such as Newton's method of finding the root of a polynomial given an approximation were extended in a classical paper by Robbins and Monro[15] to include the case where the dependent variable was a random variable. Thus, instead of solving for a root of $f(x) = \alpha$, the problem was to define a sequence (x_i) for which the sequence of expected values $f(x_i)$ approached α. This method, under the name of stochastic approximation, has since been extended by Kiefer and Wolfowitz to more general problems and by Blum to multidimensions.[16,17] The first significant practical application of these methods was in the areas of pattern recognition and automatic control. A theoretical background for these applications was developed by Albert and Gardner and by Widrow.[18,19]

Many aspects of the adaptive method make it a desirable area of study for potential elimination of problems arising in multichannel filtering of seismic data. The two most obvious and practical problems are time-varying noise fields and the high cost of filter design. Thus, the objective of the present study is to provide a theoretical and technological basis from which sophisticated adaptive systems can be implemented on line.

B. OUTLINE OF PRESENT WORK

The basic adaptive algorithm under investigation in this report is given by

$$\underline{a}(t+1) = \underline{a}(t) + 2 k_s \epsilon_t \underline{x}_t$$

where

$$\epsilon_t = d_t - \underline{a}^T(t)\, \underline{x}(t)$$

The vectors $\underline{x}(t)$ in the present application are consecutive segments of a stochastic process; $\underline{a}(t)$ is the filter applied at time t; d_t is the desired output at time t; and ϵ_t is the error in predicting d_t.

The parameter k_s may be fixed throughout the processing, may vary as a specified function of time, or may vary as a specified function of time and the data to be processed. Small values of k_s result in a slow rate of convergence, but there is little variation about the optimum, once the algorithm has converged. Large values of k_s provide more rapid convergence but produce undesirable, large variation about the optimum filters.

Theoretical studies have been directed toward problems considered to be of practical importance such as relating the rate of adaption to a system time constant, convergence, automatic control, and extending the adaptive algorithm to signal-extraction problems.[14, 20] A system time constant would indicate the effective amount of data being used; therefore, the rate of adaption could be used to control the amount that the resulting filters would vary from the optimum.[21] Theoretical conditions insuring that the adaptive technique produces the optimum filter weight have not been established.

It becomes obvious after review of actual results that, although academically interesting, theoretical work on this problem should be discontinued in favor of more practical areas of research in the adaptive field. Automatic control of the rate of adaption is desirable because the filters eventually fluctuate around the optimum with the degree of fluctuation proportional to the rate of adaption; thus, when the filters have "converged," a reduction in the adaption rate is desirable. Conversely, after a history of stationary data, if the data statistics become time dependent, a relative increase in the rate of adaption is desirable.

The only obvious application of the adaptive method to conventional Wiener filter design requires an observed desired output. Prediction-error filtering satisfies this requirement, but conventional Wiener filter design only requires a conceptual signal time trace with numerically known statistical properties. One way to eliminate the necessity of a desired signal output trace has been established by relating the adaptive method to classical methods of matrix inversion. Nonstochastic signal-model problems, e.g., maximum likelihood, can be solved by minimizing the output power of a multichannel filter satisfying a general system of constraints.

These theoretical studies have been augmented by practical experience in applying the adaptive technique to data from a variety of seismic-array configurations.[14,22] Adaptive multichannel prediction-error filtering has been compared to conventional optimum Wiener filtering for 10 sets of array data. A program for adaptive maximum-likelihood signal extraction has been developed and applied to three sets of data.

C. RESULTS AND INTERPRETATION

Major results of both prediction error and maximum-likelihood adaptive filtering indicate that adaptive filter design can be achieved in multipass off-line processing to produce filters equivalent in mean-square-error to the conventional Wiener filters. Simulation of the on-line adaptive process indicates that adaptive processing effectively reduces problems with time-varying noise fields.

In steady-state adaptive processing, the amount by which the mean-square-error exceeds the minimum mean-square-error is defined by Widrow to be the "excess mean-square-error" due to adapting the filters.[19] Widrow shows, under extensive assumptions, that the excess mean-square-error M is given by

$$M = k_s \sum_p \lambda_p$$

where the λ values are the eigenvalues of the covariance matrix Φ of the data to which the filters are applied and k_s is an algorithm parameter which multiplies the gradient at each step to obtain the additive correction to the filter weights. Thus, for normalized stationary data,

$$M = k_s \cdot \text{(no. of channels)} \cdot \text{(filter length)}$$

The actual excess mean-square-error curves are indeed linear with the k_s and roughly agree with the theoretical result for data which have been prewhitened. Adaptive processing of unprocessed data, however, reveals an interaction phenomena between fast adaption rate and oversampled data. This interaction produces a false or tracking decrease in the measured adaptive error output power.[23] This reduction is highly dependent on the number of channels and indicates that extreme care must be exercised in interpreting mean-square-error values for moderate to fast rates of adapting. Mean-square-error as a function of k_s is shown in Figure IV-1. Two independent channels of stationary data are generated from each of three spectral densities. The three spectra are 1) uniform out to the folding frequency, 2) uniform to 1/4 of the folding frequency, and 3) uniform to 1/20 of the folding frequency. Thus, the cases represent data which have not been oversampled and data which have been oversampled by a factor of 4 and 20. In each of the three cases, a symmetric 21-point filter is adaptively applied to one channel to predict the other. The optimum coefficients are 0, since the channels are independent, with a corresponding mean-square-error of 1.0. Measured mean-square-error decreases as k_s increases for the oversampled data and increases with increasing k_s for the data which have not been oversampled. The experiment has been repeated for seven channels of independent data oversampled by a factor of 20 and not oversampled. A 3-point filter has been used,

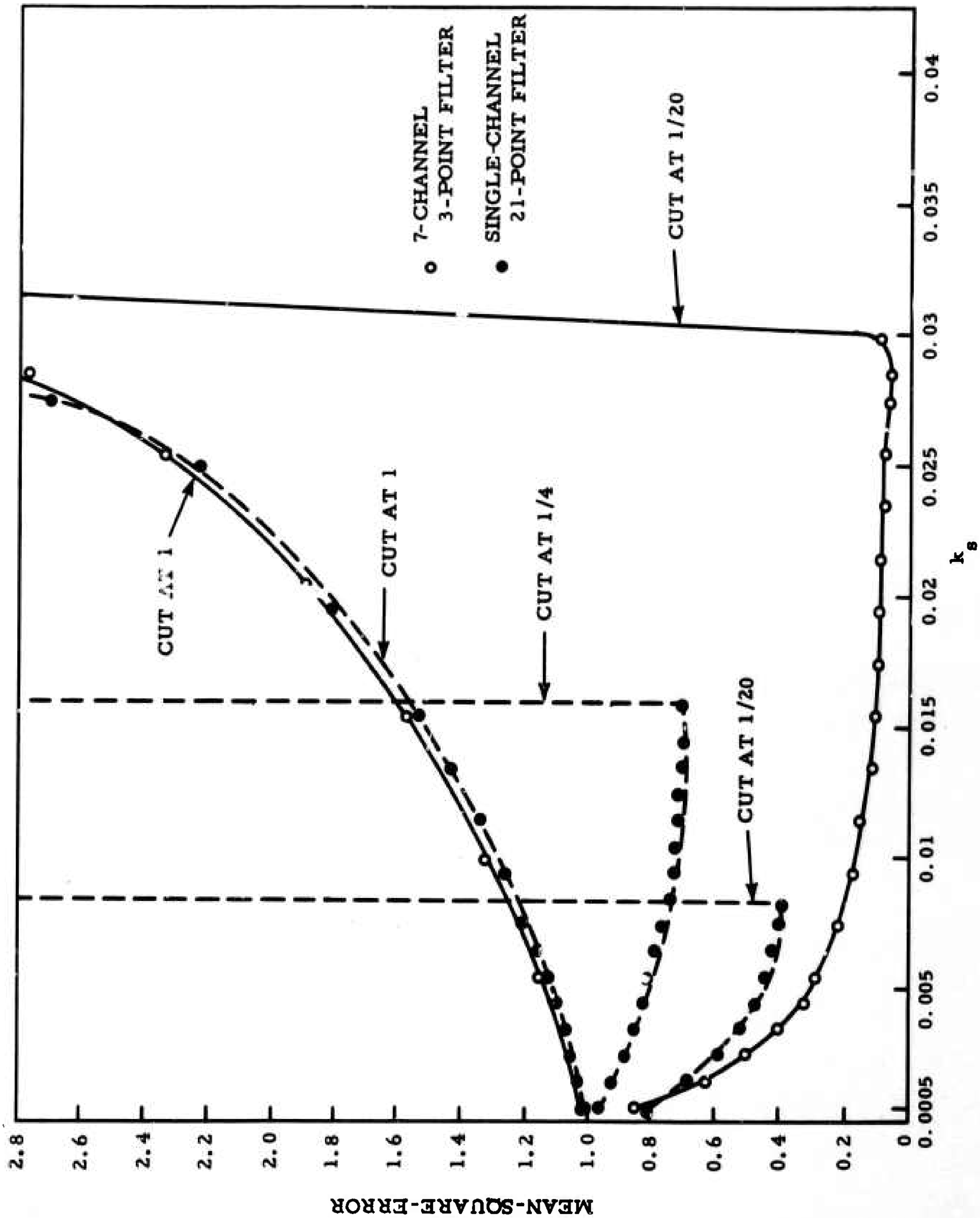

Figure IV-1. Interaction of Oversampling and Adaptive Prediction so the total number of coefficients remains unchanged. The mean-square-error curve for the data not oversampled is not significantly changed; for the oversampled data, however, the total decrease in mean-square-error is much more severe for seven channels than for the 1-channel problem.

Application of the adaptive maximum-likelihood method to a composite of five noise samples illustrates an interesting and consistent difference in error-frequency content between the adaptive and conventional Wiener methods.[22] Although the total mean-square-errors are very nearly the same, the adaptive method is better at high frequencies (as illustrated in Figure IV-2) and is worse at low frequencies. Power spectra are shown for the prewhitened data and error traces resulting from four processing techniques. The first two techniques are the straight stack (sum) and the application of fixed filters as determined from a theoretical signal model and the actual noise statistics. The last two techniques are the running adaptive (time-varying filters) and fixed filters (maximum likelihood) determined by the adaptive algorithm.

Theoretical results under believable assumptions have been difficult to achieve. One important approximation is an expression for the dependence of a time constant τ upon the rate of change (k_s) of the set of coefficients. The concept of time constant presently used is that relating to the exponential decay in the weighting of data. The effective time constant of the adaptive algorithm is the reciprocal of k times the average value for the sum of squares of data being filtered.

Another important theoretical result relates any stepwise adaptive gradient method to the set of classical techniques for iterative matrix inversion.[24] This result extends the class of conventional, adaptively solvable Wiener problems to include arbitrary signal models. Computational efficiency can be achieved through this approach if the desired signal-model covariance can be closely approximated by a matrix which has a small rank compared to the dimension of the filter vector.

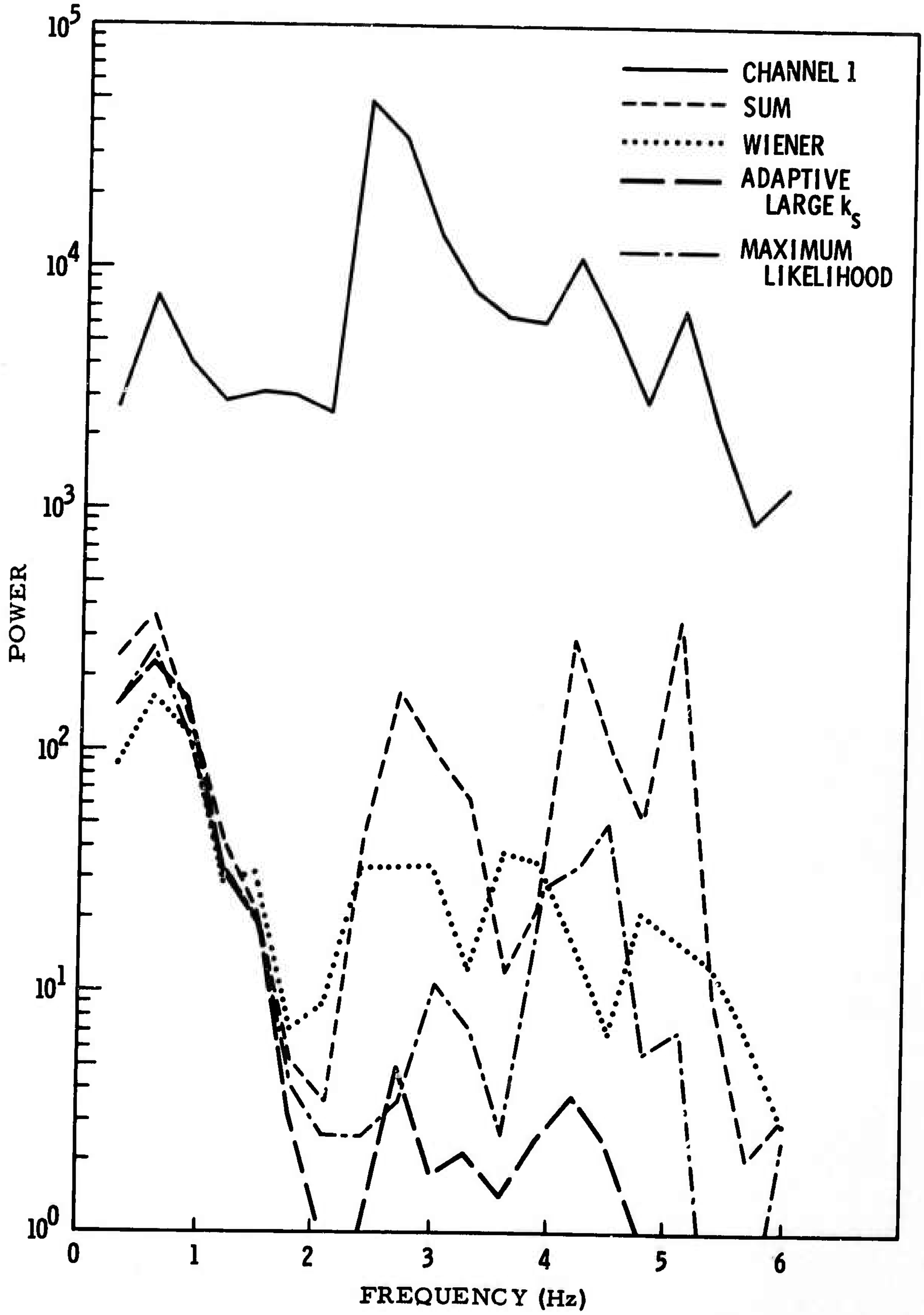

Figure IV-2. Error Power Spectra for Compared Filter-Design Techniques, Noise Sample 4

A program for adaptive computation of high-resolution wavenumber spectra has been written but not completely debugged. The theoretical basis for this program was included in a special report.[23] Effect of local noise, on multichannel filter design, i.e., noise attenuated over array distances or not propagating as plane waves, was estimated by designing a local noise model and computing the theoretical signal-extraction error for processing data containing varying amounts of local noise.

On the basis of limited data processing, the conclusion was that local noise should not seriously invalidate conventional multichannel filtering. This task was limited in scope, because part of the effort originally intended for the local noise study was shifted to the study of adaptive processing.

D. SUMMARY AND RECOMMENDATIONS

In summary, adaptive prediction MCF filters are less expensive to design, can now be implemented on line, and are potentially much more efficient for time-varying noise fields than are the classical Wiener filters.

TI studies to date have concentrated on prediction-error filter design by the adaptive technique. Signal extraction by maximum-likelihood processing has been performed in a limited number of cases, and the method has been successful as anticipated from the results in adaptive prediction-error filter design.

The adaptive method is limited to the above cases by practical experience only. The algorithm for adaptive signal extraction, given a theoretical signal model, is a straightforward generalization of the prediction algorithm. Practical usefulness of this extension depends on the development of suitable methods of signal-model representation.

Adaptive signal extraction by the maximum-likelihood method has been theoretically extended to more general signal models by adding constraints for passing multiple signals or for rejecting noise which may be modeled as discrete points in wavenumber space.[22] Application of this multiple-constraint maximum-likelihood method should be made, for example, to separate or possibly reinforce the up- and downtraveling waves in vertical arrays. Thus, both the Wiener and maximum-likelihood approaches to adaptive signal extraction should be studied to provide an adaptive filtering capability equal in range to conventional filtering but having advantages in efficiency, potential on-line use, and operating characteristics.

To realize the full potential of adaptive systems for processing array data, the continuation of adaptive signal-extraction studies, supporting research for on-line implementation of the adaptive algorithm, and general theoretical research on adaptive methods is therefore recommended.

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SECTION V

INTRA-ARRAY EQUALIZATION AND STATISTICAL STUDIES

The goal of this task as expressed in the work statement was to continue studies of the instrumental equalization problem, apply any new techniques available for studying instrumental equalization, and evaluate the effectiveness of such techniques.

To understand the direction that the research has taken on this task, one must first understand the nature and effects of the instrumental equalization problem. This problem deals with the fact that actual seismometer array data are only an approximation to ideal array data, where all sensors are perfectly calibrated and exactly located in or on a perfectly modeled wave-propagation medium. For most simple models of the elastic medium such as an homogeneous layered medium or a spherically layered earth, the signal waveform from a distant source is generally assumed to be identical on each seismometer except for a time delay which can be calculated from knowledge of the signal direction and velocity and the array geometry. In practice, recorded signal waveforms differ in amplitude and shape from seismometer to seismometer and, as well, fail to have the precise time-shift schedule that plane-wave motion should have. Often, these variations from the ideal are sufficiently small that simple, insensitive array processing techniques such as time-shift and sum work well. When sophisticated high-gain methods such as Wiener or maximum-likelihood processors designed from measured noise are used, however, unequalized array data produce deleterious effects in the design of the multichannel filters. These effects are usually noticed only when the filters are applied to data not involved in the filter design; in fact, when the filters are applied back to the data from which they are designed, their apparent performance is often appreciably better than their actual performance on new data. The unrealized portion of the apparent performance of the designed multichannel filters is called false gain.

A principal source of false gain is due to inequalization of seismometer gains in an array. In designing a maximum-likelihood filter for enhancement of a vertically arriving teleseism, the signal is modeled as being identical and simultaneous on all channels. The noise statistics are usually measured from recorded noise data. If the array data are not well-equalized, actual signals will not be identical on each seismometer and the maximum-likelihood filter will distort the signal waveform. In fact, for poorly equalized data, the actual signal may have more of the statistical characteristics of the measured noise than of the idealized signal model; then, the multichannel filter would reject the actual signal. If only the recorded noise data and the idealized signal model were used to measure the signal-to-noise ratio improvement of the multichannel filter, the true performance of the filter would be overstated. Moreover, this theoretical performance would be higher in general than the true performance of the filter designed from perfectly equalized noise data, because unequalized noise array data tend to be more different, statistically speaking, from a perfectly equalized signal model than do equalized noise data. Thus, there is increased statistical separation upon which the multichannel filter can work between the ideal signal and the unequalized noise. In fact, theoretically measured performances of sophisticated multichannel processors may be quite misleading, not only in terms of their actual performance but in terms of how well a properly designed filter can perform on the given signal and noise problem.

The inequalization false-gain problem has been studied extensively in the past, and a reasonably good practical solution known as gain slop was developed in 1964.[25] However, this solution of incorporating statistical gain inequalization into the design of the filters limits the maximum performance of the multichannel filter system. Thus, recent research has been directed toward finding a more deterministic solution in order to achieve higher array gains.

Subsection A of this section presents the results of investigating the usefulness of group coherence and group-coherence filters in studying seismometer inequalization. Subsection B discusses the results of a study of statistical false gain, a quantity which is easily confused with inequalization false gain.

A. STUDY OF GROUP-COHERENCE FILTERS AND THEIR WAVENUMBER RESPONSES

An attempt to study seismometer inequalization through use of group coherence and group-coherence filters has been made under this contract. Group coherence, a generalization of the well-known concept of coherence between a pair of stationary time series, consists of defining the coherence between two groups of stationary time series. One of the simpler definitions of group coherence, which uses the definition of coherence between two single traces, is as follows. Assume that an arbitrary multichannel filter H is applied to one group of time series to produce trace h and that a second arbitrary multichannel filter G (the input of which is the other multiple time series) has an output g; the group coherence between the two sets of time series is the maximum coherence between g and h obtainable by varying G and H, and these maximizing multichannel filters G and H are called the group-coherence filters.

An important property of coherence is its invariance with respect to linear filtering; i.e., the coherence between two traces is unchanged by passing them through frequency filters that do not have zero response at any frequency. (The filtering is reversible.) A similar, more general statement is true about group coherence: it is invariant with respect to any nonsingular linear transformation of the traces within the two groups; i.e., group coherence is unchanged by scaling, by frequency filtering, or by combining the traces within a group by any linear reversible network filter.

With regard to seismometer arrays, the group coherence between two arrays is independent of any inequalization problems possessed by the seismometers in the arrays. The two maximum coherence time traces generated from the two arrays are invariant with respect to inequalization (invariant outside of arbitrary frequency filtering of each of the two traces). This basic invariance of group coherence with respect to seismometer inequalization gave rise to the research reported in a special report.[26] If an array of seismometers is partitioned into two groups and a set of multichannel filters is designed for each group so that the coherence between the two MCF outputs is a maximum, the wavenumber responses of both MCF sets should tend to peak and be highly similar in regions where the wavenumber power spectrum is a maximum. In particular, the wavenumber response of the difference between the two MCF sets should have a small power response at the wavenumber peaks. Thus, highly coherent energy such as that generated by storms or earthquakes would appear as regions of low power response in the wavenumber response of the difference. The broader object of this study was to investigate:

- Whether the wavenumber response of the difference MCF can be used as a tool for detecting and isolating regions of highly coherent energy

- Whether multichannel filter weights can be used for determining the amplitude and phase response inequalizations of the array seismometers

Used in the study were data from the TFO long noise sample.[27] Also used were synthetic data modeled to resemble the TFO data but without any seismometer equalization problem. The research led to the following results.

The group-coherence technique is excellent for measuring the basic similarity between two arrays of seismometers, and multichannel filters are useful if the object is to generate the maximum coherent MCF outputs. Using the difference wavenumber power response, a reasonable estimate of the noise wavenumber power spectra can be made; in fact, this group-coherence wavenumber spectral estimate can be shown to include and be a generalization of one version of the high-resolution wavenumber spectral estimation studied in Task A of this contract.

The group-coherence concept appears to be of little value in determining seismometer inequalization — at least between array groups having little spatial separation such as that involved at TFO. This conclusion is based largely on the fact that the wavenumber response of group-coherence filters lacks the resolution and accuracy needed for determining seismometer inequalization. Seismometer inequalization has only a second-order effect on the wavenumber responses.

B. STUDY OF STATISTICAL FALSE GAIN

Even for perfectly equalized data, a multichannel filter designed from a sample of array noise data will have an inherent "false gain." This false gain, of a statistical nature, is due to having only a finite amount of noise data for design of the filter weights. Because only an estimate of the true noise statistics can be obtained from a finite noise sample, the resulting multichannel filter can be only an estimate of the optimum filter; thus, it has a poorer than optimum performance, at least on a long-term basis. However, if the filter is theoretically evaluated by applying it back to the data from which it was designed (and optimized for), its apparent performance will probably be superior to its actual long-term average or true performance. In fact, this measured performance will probably be higher than the true performance of the optimum multichannel filter. Thus, because of finite accuracy statistics, filter design and performance measurements have the same characteristics as possessed by filters designed from unequalized data. Since both types of false gain are similar, occur simultaneously, and undoubtedly are mistaken for each other, a study of unequalization problems must involve a study of statistical misdesign problems.

The study of statistical false gain has been very fruitful, as reported.[21] The primary goal of the study — namely that of understanding and presenting practical guidelines for controlling statistical misdesign and evaluation of multichannel filters — has been achieved. These guidelines, which are most easily expressed for the situation where the multichannel filters are being designed in the frequency domain from estimated crosspower spectral matrices, are obtained from the probability distributions of two parameters, α and β, under the Gaussian probability distribution assumption. The parameter α is the ratio of the true performance (the long-term average mean-square-error) of the designed filter to that of the optimum filter. Thus α, which cannot be less than unity, measures how much poorer is the designed filter than the optimum filter. If the true statistics of the noise are unknown (otherwise, why measure them?), the value of α for any particular design effort is unknown. One cannot be assured, therefore, that a particular filter is well-designed. However, the probability distribution of α is known, so one can make statements such as being 90-percent confident that the designed filter is within 1 db of the performance of the optimum filter.

The parameter β, which is independent of α, is the ratio of the regression error of the designed filter (the performance of the filter as estimated by applying it back to the data from which it was designed) to the true performance of the optimum filter. Since the regression error is a measurable quantity, the parameter β is useful in estimating the true mean-square-error of the designed filter in an absolute sense. Again, the value of β in a particular design effort is unknown but, from knowledge of its probability distribution, one can establish confidence limits.

Figures V-1 and V-2, taken from a special report, show the probability densities of α and β.[21] Both figures are for a 12-channel problem and show probability density functions for various values of n, the number of complex degrees of freedom being used in the multichannel filter design. As n increases, the probability density functions become more peaked and move closer to unity; this is to be expected since use of more and more data in designing a filter produces a more nearly optimum filter. Note that the true auto- and crosspower spectra or auto- and crosscorrelations of the noise array data do not affect the parameters α and β. This should be surprising and is indeed fortunate, since it means that a statistically meaningful noise-measurement experiment can be planned before any measurements are taken; i.e., for a particular multichannel filter design problem, the required amount of noise data to obtain accurate results can be specified. Conversely, given a particular amount of data, one can judge how sophisticated the multichannel filter can be before statistical false gain and misdesign become too severe a problem.

The basic guideline from this work can be simply stated: the time-bandwidth product of the design effort should be several times the number of channels in the multichannel filter. Time-bandwidth product means the product of the time length of the multichannel data sample and of the frequency bandwidth or resolution used in estimating the auto- and crosspower

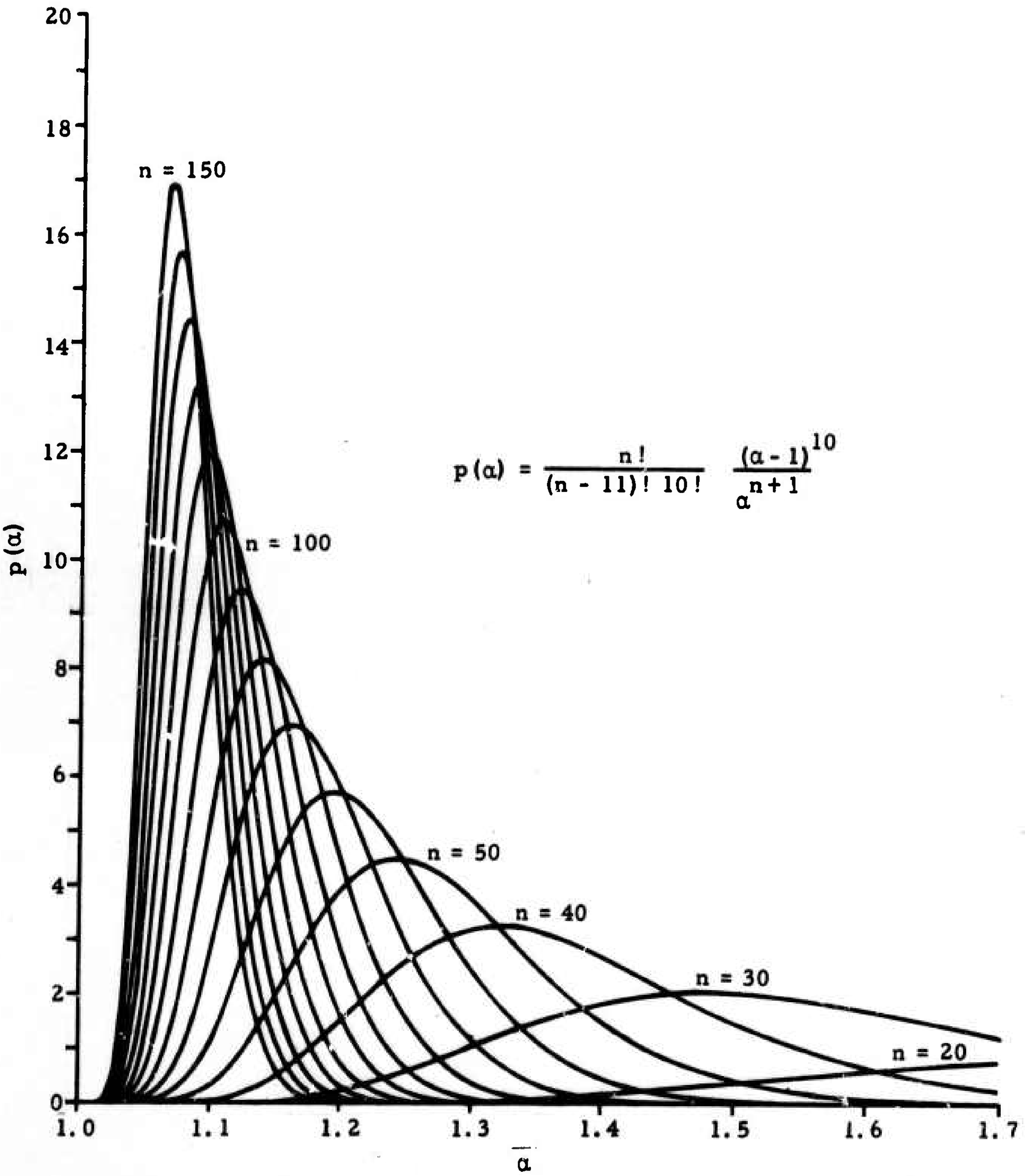

Figure V-1. Probability Densities of α for c = 12 Channels

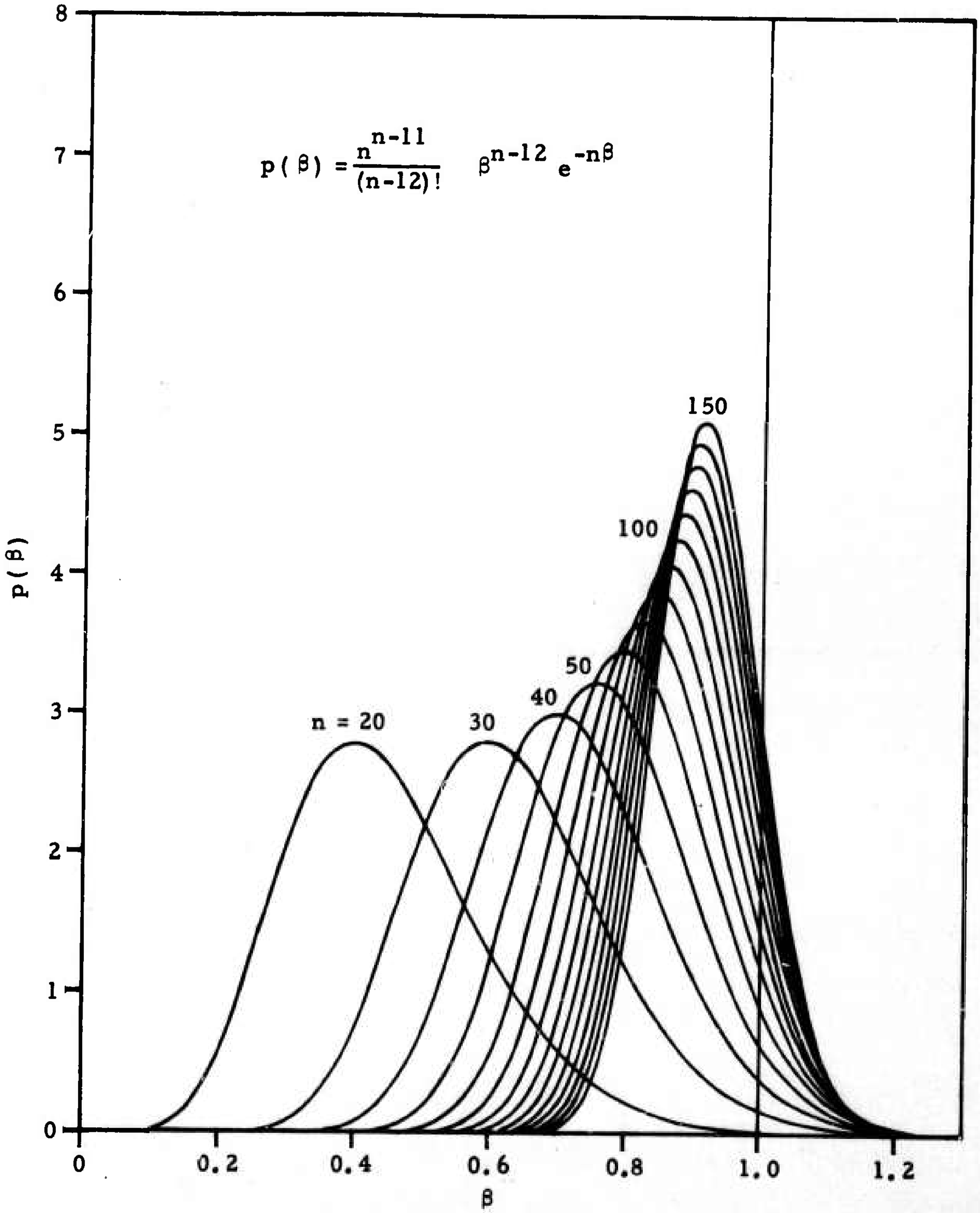

Figure V-2. Probability Densities of β for c = 12 Channels spectra. This time-bandwidth product is the number of complex degrees of freedom (i.e., n in Figures V-1 and V-2) used in the design of the filter. Roughly speaking, 10 complex degrees of freedom per channel means that the designed filter will be within 0.5 db of optimum 80 percent of the time. A time-bandwidth product of five times the number of channels gives a design within 1 db of optimum, with 80-percent confidence. These results, when combined with the cost of data recording and processing, should result in a cost-effectiveness approach to filter design.

C. CONCLUSIONS AND RECOMMENDATIONS

The use of the concept of group coherence does not appear to be very helpful with respect to the inequalization problem — at least between array groups having little spatial separation. Possibly, the analysis technique would be more successful on two array groups having 10-km to 50-km separation. The coherence measurements on such distance arrays would be interesting in themselves.

The most promising new technique for correcting seismometer responses appears to be minimum-phase equalization.[28] These filters, which are designed on the assumption that the needed correction is minimum phase, appear to equalize first motion very well. It is recommended that further work with these filters be investigated.

Confidence curves for designing statistically reliable multichannel filters in the frequency domain have been worked out very successfully. For frequency-domain-designed filters, one can now evaluate the statistical accuracy of past work and insure meaningful results in the future. Continuing research in this area is needed to investigate similar results for time-domain-designed filters. Currently, the statistical reliability of time-domain-designed filters can only be estimated from the frequency-domain results.

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APPENDIX

SUMMARY OF ADVANCED ARRAY RESEARCH SPECIAL REPORTS

CONTRACT NO. F33657-67-C-0708-P001

APPENDIX

SUMMARY OF ADVANCED ARRAY RESEARCH REPORTS

1. 18 September 1967 — Special Report No. 1
Adaptive Filtering of Seismic Array Data

Adaptive multichannel prediction filtering has been completed on four data samples, and adaptive maximum-likelihood signal extraction has been performed on one sample.

Comparison of adaptive results with those obtained from processing the same data with stationary filters (nonchanging filters designed from correlation-function estimates) shows that the adaptive filters approach the stationary filters as k_s (the rate-of-convergence parameter in the adaptive algorithm) approaches 0. For larger values of k_s, adaptive prediction-error filtering does better than stationary filters on nontime-stationary data, but stationary filters are better on data samples which appear to be time-uniform.

The performance of an adaptively designed maximum-likelihood filter was shown to be essentially equivalent to that of a maximum-likelihood filter which was conventionally designed from correlation-function estimates.

2. 30 September 1967 — Special Report No. 2
Analysis of K—Line Wavenumber Spectra from Three WMO Noise Samples

Three 1962 noise samples from WMO were studied using K-line spectra as the analytical tool. This high-resolution technique reveals noise-structure details not previously available. The purpose of the work was to provide a better understanding of the WMO noise for use in conjunction with a proposed study of arrays of horizontal and vertical seismometers.

A significant result of the analysis was the identification of broadband (0.2 to 1.0 Hz) surface-wave energy coming from the northeast. This is in sharp contrast with the narrowband character of surface-wave noise observed at other stations. The relative freedom from high-frequency attenuation of this energy suggests a near source. Two lakes located 5 to 8 km northeast of the center of the array are probable sources of this energy.

The other major noise component identified is high-velocity energy (greater than 8 km/sec). Limited spectral resolution of the array prevents determination of the precise speed and direction of this noise.

A third minor noise component of the array appears at frequencies between 0.6 and 1.0 Hz. It travels at surface-wave velocity and, while generally isotropic, appears to be somewhat concentrated in the southwest.

Above 1.0 Hz, the peaks of the K-line spectra become disorganized and a meaningful analysis is difficult. It is possible, however, to locate the direction and velocity of the characteristic 2.0-Hz energy precisely to points of ambiguity imposed by the aliasing properties of the array geometry. Three possible source directions have associated velocities within the expected range for surface waves.

Calibration data used in the computation of the absolute power levels in this report are subject to question. Therefore, the spectra should be considered accurate only in their relation to each other.

3. 8 September 1967 — Special Report No. 3
Statistics Governing the Design and Performance of Noise-Prediction Filters

In designing a digital multichannel filter from a limited sample of noise, a highly important parameter, α, is defined as the true mean-square-error of the estimated filter (i.e., the average long-term performance of the filter obtained from the noise sample) divided by the true mean-square-error of the optimum filter.

The value of α, which is equal to or greater than 1, is not known before or after an experiment since the true covariance of the data is required to calculate its value; however, the probability density of α turns out to be invariant with respect to the true covariance and depends only on the amount of data and the number of channels in the filter. Thus, one can determine before collecting any data how long a sample is needed in order to design a filter which is within 1 db (for example) of optimum with 90-percent confidence. A second similar parameter, β, defined as the estimated mean-square-error of the estimated filter (i.e., the regression error) divided by the true mean-square-error of the optimum filter is highly useful in deciding the reliability of the apparent effectiveness of the designed filter.

The probability densities of α and β are derived for the Gaussian assumption and graphs useful in experiment design are presented in this report.

4. 30 September 1967 — Special Report No. 4
Study of a 1-Point Adaptive Filter

The design and evaluation of optimum, time-invariant filters (the classical approach to prediction problems) are subject to several limitations. Because of these limitations, an adaptive system was considered. This report describes a filtering system which can adjust to changes in either signal or noise, thereby overcoming many difficulties of time-invariant filtering. The small amount of required computational time to update the filter weights is another important feature of the scheme presented.

In this report, an adaption algorithm applied to a simple time-series model was studied. For the case of stationary data, a tradeoff between the adaption rate and the mean-square-error performance of the filter exists. The adaption rate is inversely proportional to the convergence parameter λ, while the mean-square-error is directly proportional to λ. For the case of nonstationary data, a tradeoff between adapting too slowly and adapting too rapidly exists. The optimum rate of adaption appears to be approximately 10 times faster than the average time rate of change in the input data statistics.

5. 12 February 1968 — Special Report No. 5
Theoretical Crosspower and Crosscorrelation between Seismometer Outputs

A general technique is presented for computing the crosspower or crosscorrelation between two seismometer outputs corresponding to an assumed frequency-wavenumber space model of the seismic activity. The propagating medium is considered to be a horizontally stratified series of homogeneous layers overlying a homogeneous halfspace. The Haskell matrix formulation of the layer problem is used to develop the necessary relationships. The method is applicable to various types of sensors such as displacement or strain, to sensors separated both vertically and azimuthally, and to the different types of wave propagation.

The report begins with a detailed development for the case of displacement sensors in a compressional or Rayleigh wave field. Both directional and isotropic seismic models are included. Next, following the same approach, results are obtained for Love waves and displacement sensors.

Finally, as an example of the generality of the method, it is extended to include strain sensors excited by compressional waves. If one is concerned with propagational modes or sensor types other than those treated here, they too can be handled in the context of this technique.

Rather than displacement or strain, practical sensors measure these quantities modified by some linear frequency filter. The trivial modification of the crosspower due to this effect is given.

A computer program embodying this theory would provide the crosspower or crosscorrelation matrices used in the design of multichannel filters for an array of seismometers. In many cases this is the best or perhaps the only practical way to obtain these matrices.

6. 15 February 1968 — Special Report No. 6
Network Studies — Noise Characteristics

Network studies are directed toward effective utilization of a collection of seismic stations as a coherent worldwide seismic network to lower the detection threshold for seismic events and improve their classification. This report presents an analysis of ambient seismic noise seen at the network level and is directed toward characterization of the network noise field. Simultaneously recorded noise samples from two VELA stations and eight LRSM stations are investigated through analysis of power-density spectra, coherence, high-resolution frequency-wavenumber spectra, and K-line spectra. The ambiguous short-period network noise field is found to be highly variable with time and with geographical position. Variations in noise power are directly related to regional storm activity. Dominant noise power at most stations is trapped-mode surface-wave energy that does not exhibit useful interstation coherence.

7. 15 February 1968 — Special Report No. 7
Network Studies — Signal Characteristics

This report presents an initial study of signal characteristics and coherent signal processing at the network level. Topics investigated include signal similarity, depth-phase detection and recognition, separation and location of events overlapping in time and space, and methods for real-time network processing and data presentation.

Large variations in signal waveform and signal-to-noise ratio (SNR) are observed across the network. Interstation coefficients of correlation for a relatively simple Kamchatka event vary from 0.54 to 0.96, with the higher correlation found for stations on the eastern North American continent. Levinson equalization filtering does not appear particularly effective at the network level in terms of improved correlation coefficients or SNR. Depth phase detection at the network level is not materially better than for selected stations, but recognition appears more reliable than for station results in general. Experiments show that overlapping events of differing magnitudes and separated in epicenter by as little as 1° can be resolved by network beamsteer and integrate techniques. Signal-enhancement procedures implemented primarily to determine the extent of signal attenuation caused by signal dissimilarity across the network indicate less than 3-db reduction in signal energy across the signal passband (for an 8-station network). Ambient noise levels and scattered signal in the P coda are reduced by 7 to 9 db, as expected for uncorrelated energy. A method of weighting stations by their SNR's emphasizes the stations with better signal estimates and yields an additional 4- to 7-db improvement in SNR at the network level.

8. 15 February 1968 — Special Report No. 8
An Evaluation of the Use of High-Resolution Frequency-Wavenumber Spectra for Ambient Noise Analysis

An evaluation of the use of high-resolution frequency-wavenumber spectra for ambient noise analysis is presented. Comparisons are made with conventional wavenumber spectral analysis using the well-documented CPO noise field. Direct-transform spectral estimates are compared with correlation-derived spectra, and smoothing effects are examined. Studies are made of filter-design signal-to-noise ratio and of reference-sensor choice. Also presented are multichannel filter response sums computed using all possible reference sensors and summed both before and after taking reciprocals. A derivation is presented for a mathematical shortcut, yielding filter responses as a simple function of transforms of the input time series. With this procedure, sums of filter responses can be computed for all possible reference sensors in roughly the time required to compute a filter response using a single reference sensor, and the resulting spectral estimate is correspondingly less influenced by sensor inequalizations and small departures from plane-wave assumptions.

9. 23 January 1968 — Special Report No. 9
Extraction of a Directional Signal from Isotropic Noise of the Same Speed

This report compares the theoretical capability of two array processors for extraction of a directional signal propagating with a given speed V. The background noise consists of isotropic organized noise, also propagating with speed V, and of a small amount of random noise. This type of problem is encountered with long-period vertical seismometers where both the signal and noise appear in the fundamental Rayleigh mode. The small amount of dispersion in the frequency range of interest is neglected, but its effects can be inferred from our results.

A 7- and a 19-element array, both arranged on a hexagonal grid, are considered. The SNR improvements for a beamsteer and for a multichannel filter processor are computed. The computations are made for several ratios of organized-to-random noise power. The spacing between adjacent seismometers is 20 km, the propagational speed V is 3 km/sec, and the frequency range of the computations is 0.0 to 0.25 Hz.

The MCF performance is always superior to that of the beamsteer processor, but the difference between the two is significant only below 0.05 Hz where neither processor yields $\sqrt{n}$ SNR improvement. A second result is that, between 0.05 and 0.25 Hz, the improvement for either processor oscillates substantially about $\sqrt{n}$. This behavior, which is easily related to the aliasing properties of the regularly spaced arrays, is also shown to be dependent on the azimuth of the signal.

10. 15 February 1968 — Special Report No. 10
Prediction Error and Adaptive
Maximum-Likelihood Processing

Adaptive multichannel prediction-error filtering is compared to conventional optimum Wiener filtering for 10 types of array data. Adaptive maximum-likelihood signal extraction is compared to Wiener filtering for three sets of data; the three sets are composed of actual signal, artificial signal with varying magnitude and velocity, and a composite of noise data. Comparison of the two methods is based on total mean-square-error and the distribution of the error power with frequency.

On-line adaptive processing will solve problems with slowly time-varying noise fields such as UBO road noise. The adaptive method is also simpler and more economical than the Wiener method as an off-line filter design procedure for array data known to be approximately time stationary.

The two methods will produce essentially equivalent filters with respect to total mean-square-error; however, relatively large differences in the actual filter response characteristics are possible.

11. 15 February 1968

Special Report No. 11
Use of Horizontal Seismometers To Enhance Signal on a Vertical Seismometer

Previous theoretical studies have indicated that arrays consisting of rings of radially oriented horizontal seismometers concentric with a central vertical seismometer are useful for the extraction of P-wave signals from Rayleigh-wave noise. Data from the horizontal seismometers are used to predict off of the Rayleigh-wave component in the vertical-seismometer trace, leaving the P-wave signal. To test this hypothesis, data were recorded from an experimental array at WMO having two horizontal rings and a central vertical seismometer. The diameters of the rings were 1.15 and 2 km. This report presents the results of processing the data.

The two multichannel processors designed were a conventional Wiener infinite-velocity signal-extraction filter and an adaptive prediction-error filter. Both processors were applied to two events and to a noise sample preceding one of the events; this noise sample had been used in the filter design. The Wiener processor, which was the better of the two, yielded about 4-db noise suppression over 0.0- to 3.0-Hz frequency range. Both processors showed some signal distortion, thereby making their performance even more discouraging.

Below 1.0 Hz, this poor performance is not surprising since, in this range, WMO is known to have a high level of P-wave noise which cannot be suppressed effectively by this type of array. At higher frequencies, however, much greater SNR improvement is to be expected. Examination of the recordings shows a great deal of variability along the individual horizontal-seismometer outputs and from output to output. This, coupled with the poor performance of the processors, suggests that the records contain a high level of nonseismic noise. In view of this, the results of the experiment are inconclusive.

12. 15 February 1968

Special Report No. 12
Minimum Power Array Processing of the TFO Long-Noise Sample

This report investigates the effectiveness of the minimum-power-array processing technique in determining seismometer inequalizations. The technique involves the partitioning of the seismometer array into two groups and the design of MCF's for each group so that the mean-square-error between the two MCF outputs is a minimum under the constraint that the output power of one of the MCF's is unity. The two MCF sets are known as the group-coherence filters; the difference between these sets is known as the minimum-power-array processor.

Estimates of the noise wavenumber spectrum from the wavenumber responses of the group-coherence filters are distorted due to seismometer inequalization; however, a more reasonable estimate of the noise wavenumber spectrum from the wavenumber response of the minimum-power-array processor should be possible because the minimas in the processor's wavenumber response correspond to the wavenumber regions where the wavenumber responses of the two group-coherence MCF's are very similar (e.g., at the peaks of the noise wavenumber power spectrum).

Seismometer inequalization was to be determined from the adjustment in weight and phase required for each filter so that the wavenumber responses of the group-coherence MCF's would agree with a reasonable noise wavenumber spectrum. However, results from the TFO long-noise sample and two synthetic models show that the technique, although excellent for generating maximum coherent channels, lacks the wavenumber resolution desired for studying seismometer inequalization. This latter conclusion is at least true for small arrays such as TFO.

13. 15 February 1968 — Special Report No. 13
Theoretical Considerations in
Adaptive Processing

The four sections of this special report represent theoretical results on four logically independent problems arising in the application of adaptive multichannel processing. Areas treated are effect of local noise on multichannel filter design, adaptive high-resolution wavenumber spectra, multiconstraint adaptive maximum likelihood, and the interaction of oversampling with rate of adaption.

Local noise was modeled to provide the covariance matrix necessary to determine the optimum Wiener filters. Filters were computed for seven levels of local noise, and the theoretical mean-square-error curves are given for the application of these curves to noise, signal plus noise, and signal plus noise plus local noise. The effect of this local noise model, when present in the design data and absent in the data to which the filters are applied, appears negligible.

A method of computing adaptive high-resolution wavenumber spectra was developed and programmed. The program was not checked out; possible level of effort rather than technical reasons made discontinuation of this problem expedient.

Some theoretical questions of uniqueness not fully answered in earlier reports on the adaptive maximum-likelihood method are considered and the method extended to multiple constraints.

Interaction of oversampling with rate of adaption is illustrated by processing results on theoretically generated data. Mean-square-error, for oversampled data, to predict one channel from a set of independent channels is shown to be monotonically decreasing with k_s to the point of instability. The severity of this effect is dependent on the degree of oversampling and on the number of channels.

14. 15 February 1968 — Special Report No. 14
An Experiment in Event Detection and Location with LASA Wavenumber Spectra

The relative abilities of the LASA and a subarray to detect and locate a weak teleseismic event through frequency-wavenumber processing was investigated. Subarray C3 was selected for subarray processing and an ensemble of 12 subarrays was selected for large-array processing. Nine of the subarrays were not used due to large traveltime anomalies and low signal-to-noise ratios.

Frequency-wavenumber spectra were computed over several consecutive noise samples and one sample containing the signal from the 25 C3 seismometer outputs and the 12 subarray straight sums. Best evidence of the event arrival was obtained from wavenumber spectra computed from subarray C3 using 5-sec data gates. The epicenter estimate obtained from the subarray spectra was quite close to the reported epicenter and compared favorably with that obtained from the large-array wavenumber spectrum. Evidence of the event was poor on the large-array wavenumber spectrum using 60 sec of data in that the peak observed due to the event was not appreciably higher than those obtained in the ambient noise spectra preceding it. Better results could possibly be obtained from LASA if shorter time gates were used.

This study indicates that a LASA subarray is probably better suited for event detection and location through frequency-wavenumber processing than is the LASA. The processing necessary to obtain wavenumber spectra from a subarray could readily be performed on line since compensation for traveltime anomalies and signal inequalities is unnecessary for arrays of this size. The much larger traveltime and signal amplitude anomalies observed for most events across the LASA make on-line detection and location at the large-array level impractical. The greater wavenumber resolution inherent in the larger aperture is completely negated by these anomalies. Use of an intermediate-size array or an extended subarray might result in a satisfactory compromise in which greater wavenumber resolution is obtained without encountering such large time and amplitude anomalies.

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Texas Instruments Incorporated Science Services Division P.O. Box 5621 Dallas, Texas 75222	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP —

3. REPORT TITLE

FINAL REPORT ADVANCED ARRAY RESEARCH

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
Final

5. AUTHOR(S) *(First name, middle initial, last name)*

Burg, John P.	Heiting, Leon N.	Johnson, William A.
Hair, George D.	Booker, Aaron H.	

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
15 February 1968	93	28

8a. CONTRACT OR GRANT NO. F33657-67-C-0708-P001 b. PROJECT NO. VELA T/7701 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) — 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* —

10. DISTRIBUTION STATEMENT
This document is subject to special export controls, and each transmittal to foreign governments or foreign nations may be made only with prior approval of Chief, AFTAC.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
ARPA Order No. 624	Advanced Research Projects Agency Department of Defense The Pentagon, Washington, D.C., 20301

13. ABSTRACT

A qualitative summary of the four principal tasks pursued during 1967 is presented. Quantitative results and more detailed descriptions of the various experiments are presented separately as a series of special technical reports. An appendix to this report lists these specials with their abstracts.

Principal tasks reported are studies of continuously adaptive data processing systems; use of multicomponent arrays of mixed sensor type; signal and noise characteristics across a worldwide seismic network; and new approaches to the intra-array signal equalization problem.

DD FORM 1 NOV 65 1473

UNCLASSIFIED
Security Classification

UNCLASSIFIED
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Advanced Array Research						
Continuously Adaptive Data Processing Systems						
Multicomponent Arrays						
Signal Characteristics						
Noise Characteristics						
Worldwide Seismic Network						
Intra-Array Signal Equalization						

UNCLASSIFIED
Security Classification